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MODERN IDEAS OF THE ATOM

HARRAP'S TECHNICAL MONOGRAPHS

EDITOR: C. L. BOLTZ B.SC. (HONS.) LOND.

MODERN IDEAS OF THE ATOM

BY

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WITH TWENTY-SIX DIAGRAMS AND TWO TABLES

GEORGE G. HARRAP & CO. LTD.

LONDON SYDNEY TORONTO BOMBAY

First published 1947
by GEORGE G. HARRAP & CO. LTD.
182 High Holborn, London, W.C.1

THIS BOOK IS PRODUCED IN
COMPLETE CONFORMITY WITH THE
AUTHORIZED ECONOMY STANDARDS

Composed in Times New Roman type and printed by Western Printing Services, Ltd., Bristol. Made in Great Britain

PREFACE

Atomic Theory, until recently the province of the physicist and chemist, has suddenly become a subject of great practical interest to the ordinary citizen, who realizes that the harnessing of atomic energy has presented to mankind the choice between good and evil in a form more acute than perhaps ever before in history. On the one hand the atomic bomb sets a new standard in indiscriminate destruction; on the other the not-too-distant prospect of industrial exploitation of this new source of power portends an era of material prosperity compared with which the present is one of feudalism.

The aim of this short monograph is, however, purely technical; it is to give the general reader as full a description as space permits of the established facts and theories which together constitute modern sub-atomic physics, and to show that recent achievements in atom-splitting are but the natural outcome of our increasing knowledge. While the book is intended to be complete in itself (within the modest scope envisaged), it is hoped that the account may serve also as a background for the understanding of other, more specialized works, including Government publications on the subject.

The material of this narrative lends itself quite readily to historical presentation, which, roughly, is the method adopted; but the author asks his readers' indulgence if, in pursuance of this plan, he has on occasion found it necessary to switch disconcertingly in tense.

Finally, the pleasure of an acknowledgment: to Mr W. G. Tallis, who prepared the diagrams.

S. L.

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PRELIMINARY HISTORY: REVISION

Origins of Modern Chemistry

Towards the end of the eighteenth century the small band of scientists, or natural philosophers, as they who carried on experimental inquiry were called, were coming to the conclusion that the almost infinite variety of substances of our material world were in reality composed of a comparatively limited number of simpler substances. These, it was thought, combined with one another to produce new varieties of matter. This belief had been carried over from the alchemists, the forerunners of modern chemistry, who, if for the most part they mixed a lot of charlatanism with a little knowledge, yet contrived to discover and record a considerable amount of disjointed information concerning what we now describe as chemical processes.

The test of whether a substance was 'simple,' or elemental, rested on experiment. A substance remained an element only as long as nothing simpler could be obtained from it. The commoner metals, such as iron, copper, mercury, and lead, were early recognized to be elements, and so was sulphur. Water was thought to be an element at one time, until Henry Cavendish (1731–1810) showed that it could be formed by exploding the gas hydrogen, which he had obtained by the action of acid on metals, together with air. Part of the air (what we now know as oxygen) disappeared with all the hydrogen, and a residue of water was left.

What was significant about this experiment was that Cavendish weighed the oxygen that was used in the explosion, and also the water formed, and found that the ratio of oxygen used to water formed was always constant. Curiously, Cavendish did not realize the full importance of his work, and it was a French chemist, Antoine Lavoisier, who gave the correct explanation.

An experiment of Lavoisier (1743–94) made clear the fundamental nature of combustion. He began with a weighed quantity of mercury, which he heated in a retort to just below its boiling-point (Fig. 1). At this temperature a red scale formed on the top of the mercury. He continued this process of heating for twelve days, and at the end of that time weighed the resultant 'calx,' as it was called. Long before this the scale had ceased to form. The red calx was found to weigh about 8 per cent. more than the original mercury. He noticed at the end of this time that one-fifth of the total air in the bell-jar and retort had been used up. Lavoisier now heated this calx to a somewhat higher temperature, when it decomposed back to the original mercury and gave off an amount of 'gaseous substance' equal in volume to that which had disappeared from the air. Also, within the limits of his experimental error, the weight of mercury recovered was equal to the weight with which he had begun. The gas given off was shown to possess all the properties of oxygen, which Priestley had discovered a few years earlier, and which Scheele, a great Swedish chemist, had shown to be present in air to the extent of one-fifth by volume.

By such experiments as these the early chemists laid the foundations of their science. Among the conclusions they established by careful quantitative experiments was one of particular importance—the Principle of the Conservation of Matter. This stated that in any chemical reaction the total

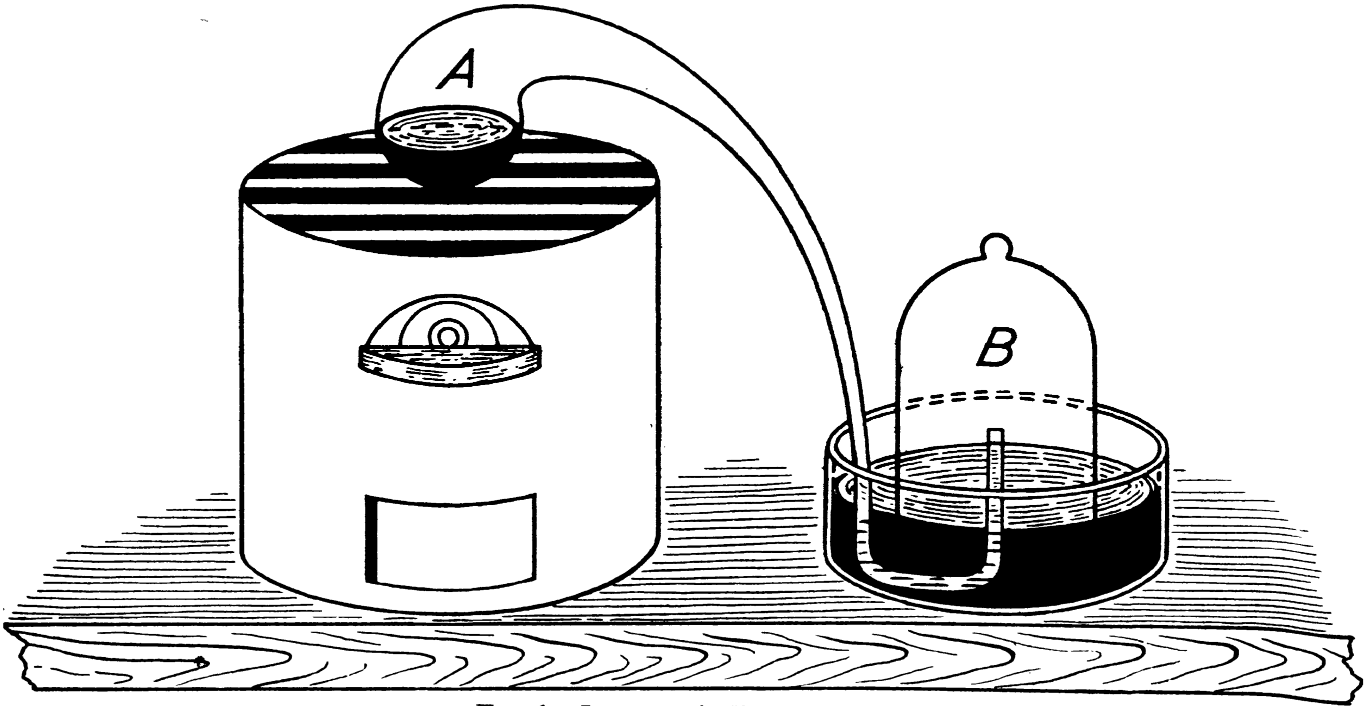


FIG. 1. LAVOISIER'S EXPERIMENT

After the mercury in *A* had been heated for twelve days a red scale formed on the surface and the mercury rose in the bell-jar, *B*. The scale was removed and heated to a higher temperature, when oxygen was given off equal in quantity to that absorbed from the air within the apparatus.

weight of the substances taking part was equal to the total weight of the products formed, no matter what change of form had resulted. There may seem obvious exceptions to this, such as the familiar coal-fire, which disappears mostly in smoke; but careful investigation has shown that if the products of combustion, such as ash and flue-residues and the invisible gas carbon dioxide to which the coal burns, are collected, then their combined weight is equal to that of the original coal, plus the air required to burn it.

Another important discovery was that these elements combined with one another in quite definite proportions by weight even when the combining was brought about in different ways. Sometimes it was found that one element (A) could unite with another (B) to form more than one compound; but when it did so the amount of A which united with a given quantity of B was always simply related in the various compounds. Thus the compounds might be $A + B$, or $A + 2B$, or perhaps $2A + 3B$, but never, say, $A + \frac{10}{11}B$. Such facts demonstrated the Law of Multiple Proportions, enunciated by John Dalton about 1806.

By this time, therefore, chemistry rested on a secure basis of established fact, and conditions were ripe for some general theory that would link up these various facts and interpret them as aspects of a single idea. Dalton supplied this idea in the Atomic Theory.

The Atomic Theory

Dalton has not left on record the precise manner in which he arrived at his theory, but it seems probable that it was through his interest in the behaviour of gases. He knew that air was a mixture of oxygen and nitrogen, and that these gases differed in density. But the composition of air seemed

to be everywhere constant; that is to say, there was no settling out of the denser gas, oxygen. He came to the conclusion, therefore, that the gases consisted of minute particles in random motion and kept mixed in virtue of this motion.

But how could this conception be extended to solids in order to explain such experimental facts as the Law of Multiple Proportions?

Dalton had only to refine his ideas by adding the further provisos that all atoms of any element were alike, and—in particular—possessed a definite and characteristic mass. Also, a ready explanation for the distinction between mixtures and chemical compounds was found by the assumption that in the former the atoms of the different substances were independent of one another, whereas in the latter they were linked together in groups of two or more. And so in the discontinuity of matter itself was found the reason for the abrupt changes in proportions of elements which united to form more than one compound.

Dalton's theory was quickly accepted among scientists, and the relative combining weights of all the known elements were soon determined.

Here came a difficulty. These equivalents, as they are termed, do not of themselves determine the relative atomic weights, for it is not always certain how many atoms of a particular element are united with another in any given compound. It was suggested by Berzelius (1779–1848) that the same volume of all gases kept under the same conditions of temperature and pressure contained the same number of atoms. This was a reasonable suggestion, if it could be supposed that atoms were small in comparison with the space that they occupied, and in a simple gas, such as oxygen or nitrogen, or in a mixture, the individual atoms had no appreciable effect on one another. There was no particular

reason, therefore, why there should be more of one kind of atom than another if they were kept under identical conditions of confinement.

Let us consider the chemical combination of the two gases hydrogen and oxygen from this standpoint. As we have seen, these gases, when exploded in the proportion of two volumes of hydrogen to one of oxygen, disappear completely and leave only water. If the gases are measured at some temperature above the condensing-point of steam, then after explosion and cooling to the original temperature it is found that two volumes of steam are formed. Thus:

Two volumes of hydrogen + one volume of oxygen = two volumes of steam.

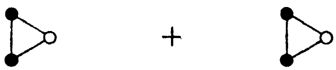
Suppose that there are a million atoms in the volume of oxygen that we are considering. Then, according to Berzelius, there will be two million atoms in the two volumes of hydrogen, and two million in the two volumes of steam. If we fix our attention on *one* atom of oxygen, therefore, it would seem that it combines with *two* atoms of hydrogen to form *two* 'atoms' of steam. But since all elementary particles of steam are alike, and since atoms cannot be divided, how can this possibly happen? Avogadro (1776–1856) got out of the difficulty in what now appears an extremely simple way. He concluded that the 'atom' of oxygen present in the original gas really consisted of two particles joined together and behaving as one, as far as its physical properties were concerned. Hydrogen he considered as being composed similarly. Thus we can represent the compound particle of oxygen as consisting of two true atoms linked together:

and hydrogen by:

According to experiment two compound particles of hydrogen have united with one of oxygen:

two hydrogen volumes one oxygen volume

Two compound particles of steam are formed. These must therefore be:



two volumes

Such compound particles are now called molecules, and the molecule of an element is the smallest 'particle' of it which can exist in the free state. Thus oxygen and hydrogen atoms do not normally exist in the free state. The modern chemist uses a rather more convenient shorthand to represent these various particles. He denotes the atom of hydrogen by the capital letter H and the molecule of hydrogen by H-H or, more usually, H_2. The oxygen atom is similarly denoted by O and its molecule by O_2. Therefore the reaction we have just considered is now written:

$2H_2$	+	O_2	=	$2H_2O$.
2 volumes		1 volume		2 volumes
4 grams		32 grams		36 grams

It is an astonishing fact that this 'obvious' explanation of Avogadro was not accepted immediately, but had to wait fifty years for its due recognition.

The above chemical equation, as it is called, really represents the behaviour of individual molecules and not large volumes, but since all molecules of any substance are identical, it serves to indicate the behaviour of all the molecules.

It can be seen, then, from what simple beginnings the Atomic Theory arose; and yet this theory dominated

chemistry throughout the nineteenth century—and still does. The reason for this is that it was a sufficiently general idea to permit of additions and modifications as time went on. The idea of the *valency* of an element was such an addition. As can be seen above, the molecule of steam, or water, is represented by the formula H_2O. Now this indicates that one atom of oxygen, O, requires two atoms of hydrogen, H, for its combination. If equal volumes of oxygen and hydrogen are exploded the compound HO is not formed—only half the oxygen disappears as H_2O, and the remainder is unchanged. This suggests that oxygen has two links with which to bind other atoms, whereas hydrogen has only one. The hydrogen molecule is therefore represented by H–H, whereas the oxygen molecule is represented by O=O, and the water molecule by

$$O\begin{matrix}\diagup H\\ \diagdown H\end{matrix}$$

The idea was extended considerably, and achieved its greatest success in the chemistry of the carbon compounds, but it is not our purpose to pursue this branch of the atomic theory.

Periodic Classification of the Elements

The only other aspect of nineteenth-century chemistry that must be mentioned before we come to the Great Age of sub-atomic discovery is the systematic grouping of the elements which was achieved by a Russian, Dmitri Mendeleev. By 1869 a considerable amount of detailed information concerning the properties of large numbers of elements and their compounds had been collected. Mendeleev tried arranging these elements in order of their atomic weights, in tabular form. But his great achievement was to arrange the table in such a way as to bring out a most interesting fact

which until then had escaped notice. This can best be understood by referring to the table which he constructed, which is shown up to date in Table II (p. 150). Reading down column one, we find a list of symbols which represent elements known as the alkali metals. In the column we find H, standing for hydrogen; Li, for lithium; Na (Latin, *Natrium*), for sodium; K (Latin, *Kalium*), for potassium; and then a branch of which the left-hand side is Rb, for rubidium, and so on.

With the exception of hydrogen, which is put in a row all to itself and is an unusual element in many ways, all these elements are known to have astonishingly similar chemical properties. All, for example, react violently with water, giving off hydrogen and forming caustic solutions. These caustic solutions react with acids to give neutral substances ('salts') and water. The reaction may be represented in our chemical shorthand by:

$$\begin{array}{llcll} & 2\,\mathrm{Na} + 2\,\mathrm{H\text{-}O\text{-}H} & = & 2\,\mathrm{Na\text{-}O\text{-}H} & + \mathrm{H\text{-}H}, \\ \text{or} & 2\,\mathrm{Na} + 2\,\mathrm{H_2O} & = & 2\,\mathrm{NaOH} & + \mathrm{H_2}. \\ & \text{sodium} \quad \text{water} & & \text{caustic soda} & \text{hydrogen gas} \\ & \text{(solid)} & & \text{(dissolves in} & \\ & & & \text{excess water)} & \end{array}$$

They all react violently with the elements known as halogens, at the far end of the table—F (fluorine), Cl (chlorine), Br (bromine), I (iodine)—and progressively less violently with elements in the intermediate columns. All the elements in column one were found to be univalent—that is, they had one bond available for linking to other elements. Similarly all the elements in the second column were like oxygen in that they were bivalent, or had two bonds available. This valency rises to four in column four, and then decreases to one in column seven.

Bearing in mind that the elements have been arranged

according to atomic weight as we read from left to right along the rows, and move from the end of one row to the beginning of the next, we see that there is exhibited a kind of periodic variation in their properties. For this reason the arrangement is known as the Periodic Table. By its means Mendeleev was able to predict the existence of certain elements at that time unknown, for he found it necessary to leave gaps in places in order to preserve elements having known similar properties in the same columns. Not merely did he predict such elements, but also many of their properties. In due course these elements were isolated and found to have the identical properties he had predicted.

This periodic fluctuation in the properties of the elements suggests that there is some underlying relationship among them. The idea had been mooted much earlier in the century (1816) by William Prout (1785–1850), who was struck by the fact that many elements had atomic weights very near to a whole number. He considered, therefore, that they might all have arisen from the element of weight one—hydrogen—and this he termed 'protyle,' the primitive substance. As atomic-weight determinations became more exact it was seen that although many elements had atomic weights very near to whole numbers, yet there were also frequent cases where this was not so. Chlorine was a particularly bad offender, for its atomic weight was found to be nearly 35½. Thus the idea was abandoned; it happened to be premature.

Recent work has cleared up these difficulties and shown that Prout was right in his instinctive belief that all matter has been built up from a more elementary substance. But this elucidation was one of the great achievements of the twentieth century, and will be dealt with later, when its significance will be better realized.

Mention must be made of the fact that careful determination of the atomic weights of oxygen and hydrogen showed

them to be not exactly in the ratio of 16 : 1. Since, however, oxygen, rather than hydrogen, was and is the element most used in determining the atomic weights of the elements, it was decided to adopt oxygen as the standard and to assign the standard value of 16·0000. On this scale hydrogen has the atomic weight of 1·0078.

It has been found that the atomic weights of many elements approximate more nearly to whole numbers if the standard O = 16, rather than H = 1, is taken. The explanation of this was also forthcoming with the advance in our knowledge of the atom.

This, then, was the position by the closing years of the last century. It was assumed that matter consisted of minute corpuscles, hard, indivisible, and immutable, which in gases could move about at random in the free state. Elements consisted of particles all of the same kind which could not by any means be converted to particles of any other kind, but could combine with other particles in various ways, to produce all the variety of substances existing in nature. This idea of the atom as a sort of solid ball represented in a way the immense and solid achievements of the Victorian Age. It was a picture of unrelieved materialism. From the valley of chaos and ignorance men had climbed to knowledge, and apparently had reached the peak. Nothing really new remained to be discovered. The scientist, as he looked back down the century, could see how his principles had become firmly established, and none more so than the Atomic Theory of Dalton. All that remained to be done in the future was to fill in the gaps and extend knowledge according to existing law.

Few foresaw the immense change to come in a few years which was to revitalize physical science.

How did this change come about? It was not due in the first instance to the chemists at all, but to the physicists—in

particular to the small group of investigators who were studying the discharge of electricity in highly rarefied gases. It is not surprising that progress came from this direction, for matter in such a highly diffused form is less complicated in its behaviour than in the state in which we normally encounter it. Consequently effects that hitherto had escaped notice became capable of detection.

Discovery of X-rays

For a number of years investigators had studied the interesting phenomena which appeared in a discharge-tube when a high voltage was operating, and in November 1895 Wilhelm Röntgen made a sensational discovery that shook the world of scientists (and laymen) when made public in 1896. He had noticed the fluorescence of some barium platino-cyanide when it was in a dark room and screened from his discharge-tube by black paper. He followed up this observation by showing that invisible rays—X-rays—were produced which could penetrate appreciable thicknesses of matter and affect a photographic plate (Fig. 2). It was eventually demonstrated that they were akin to light waves, but of much smaller wavelength. Their properties were therefore explicable in terms of Maxwell's Electromagnetic Theory, and, indeed, their existence provided a confirmation of that theory. We shall have occasion to refer in greater detail to some of the properties of X-rays later.

The Electron

A discovery less sensational at the time, but which afterwards acquired an even more fundamental significance, was that of the electron—by Sir J. J. Thomson, in 1897. Here again the phenomenon became manifest in the discharge-

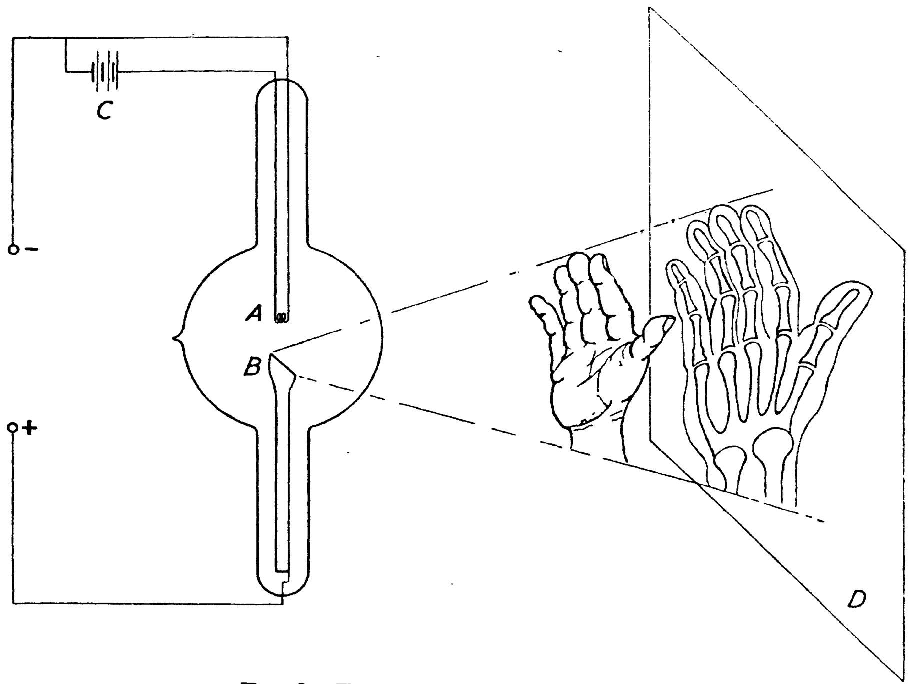


FIG. 2. THE PRODUCTION OF X-RAYS

The filament *A* in the evacuated bulb is heated by the battery *C*. A high voltage operating between *A* and *B* drives electricity with great force from *A* to *B*. X-rays are generated at *B* and fall on the fluorescent screen *D*. An object interposed between *B* and *D* will cast a shadow on the screen, the denser part of the object—*e.g.*, the bones of the hand—absorbing the rays more than the less dense and giving a darker shadow.

tube, and the electron was first recognized in the so-called cathode rays. Whereas it could be shown that X-rays were given off from the target which had been bombarded with the cathode rays (by altering the direction of the reflecting surface of the target, for example), the electrons themselves actually constituted the cathode rays. They differed from X-rays in that they could be deflected by electric and magnetic forces, applied across their direction of motion, whereas X-rays are undeviated under such conditions, behaving like light in this respect.

Thomson utilized this property to estimate the weights and the electric charges of the particles. If an electric charge —say, a negative charge on a particle—is placed between two parallel metal plates, one of which is connected to the positive end of an electric battery and the other to the negative end, the negative particle will tend to move to the positively connected plate, and hence away from the negative plate. On the other hand, if such a particle is made to pass between the poles of a powerful magnet it will be attracted to neither, but will try to move sideways—*i.e.*, at right angles to its initial direction of motion. It will be seen that by the application of a magnetic field (as it is called) at right angles to an electric field it is possible to make one oppose the other, or reinforce it at will. Thomson arranged his apparatus, as can be seen in Fig. 3, so that one field could be used to counteract the effect of the other if desired.

By balancing the electric strength (X) against the magnetic strength (H) Thomson was able to find the velocity of this stream, for it may be shown that the velocity (v) is given by

$$v = \frac{X}{H}.$$

Now by using a magnetic force alone, and noting the deflection of the rays on the fluorescent screen, he was able

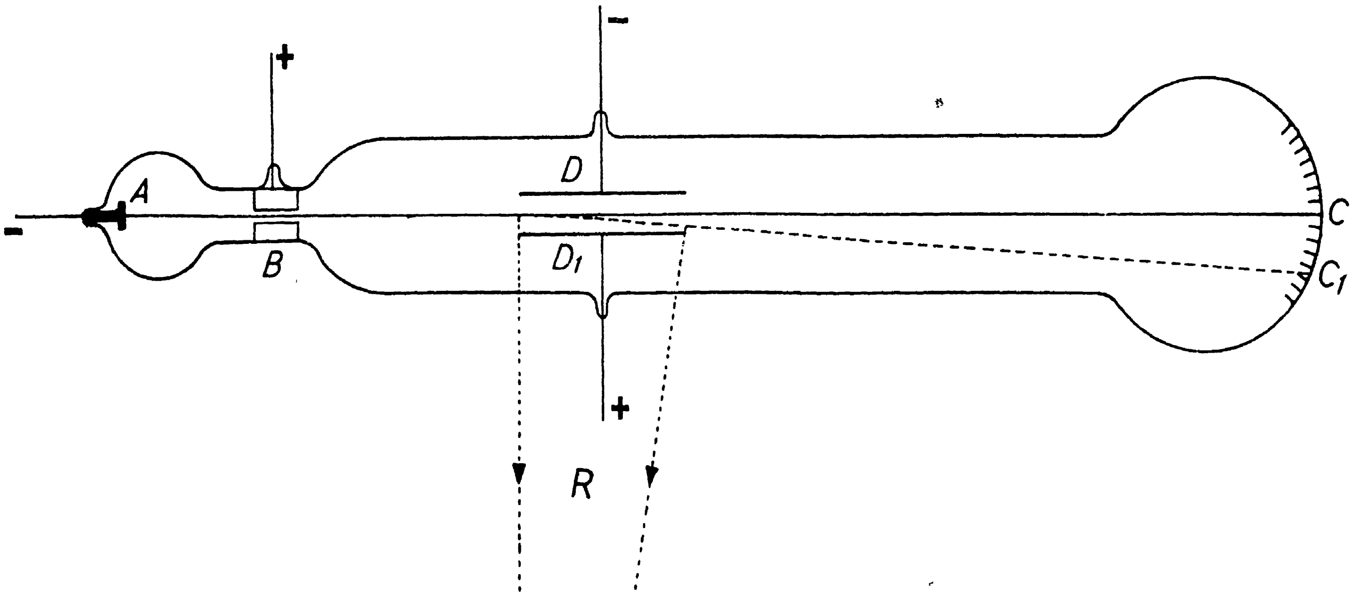


FIG. 3. ESTIMATING THE CHARGE ON THE ELECTRON

Electrons generated at the cathode, A, pass through the pierced anode, B, and, if not deflected, strike the fluorescent graduated screen at C. Across D and D_1 is applied an electric field which deflects the electron beam to C_1. The magnets (not shown) are applied at position D, but with their pole surfaces in the plane of the paper. While passing through the plates the electrons describe a curved path of radius R.

to determine the ratio of the charge (e) on the particle to its mass (m), for

$$\frac{e}{m} = \frac{v}{Hr},$$

where r is the radius of the circle which the particle describes under the influence of the magnetic field (H), and is measured on the fluorescent screen, which is scaled for the purpose.

Thus, knowing H and being able to calculate the velocity (v) from the first expression, he was able to determine the ratio $\frac{e}{m}$.

It was plain that before either e or m could be determined separately further information was necessary, and Thomson could not see how it was to be obtained from cathode-ray experiments. It was known, however, that X-rays, when used to irradiate a gas, rendered that gas conducting to an electric current, and this was ascribed to the ionization of the gas—that is to say, to the electrical charging of the atoms. He measured the charge carried by these 'ions'—by a method utilizing a singularly beautiful technique invented by C. T. R. Wilson—that of the cloud chamber.

The Wilson Cloud Chamber

Briefly it is this. An atmosphere absolutely free from dusty particles and saturated with water vapour is allowed to expand suddenly. Expansion normally produces cooling, and in the presence of small particles which act as nuclei for the condensation a cloud is formed. But in the absence of any such nuclei the atmosphere remains perfectly clear, despite the drop in temperature. It is in a state known as super-saturation.

Now it was found that these charged atoms, or ions, were

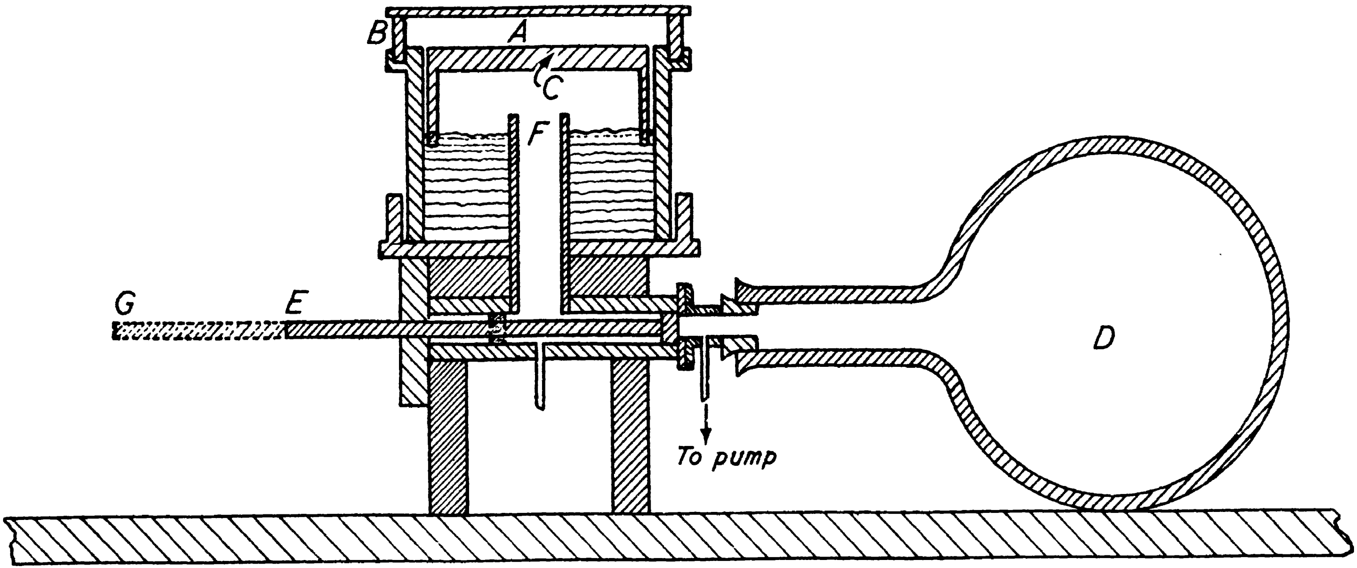


FIG. 4. AN EARLY FORM OF CLOUD CHAMBER

Air saturated with moisture, *A*, is confined within a glass cover, *B*, and a brass piston, *C*. The vessel *D* is kept evacuated with a water-pump. When the piston *E* is drawn back to the position *G* air rushes into *D* from *F* and the piston, *C*, falls suddenly. The sudden expansion cools the air in *A* and supersaturates it. A small pencil of rays directed into the chamber from the point *B* will cause minute cloud streaks to form, which can be photographed from above.

as effective as dust particles in promoting condensation of water vapour under such conditions. The cloud chamber (as illustrated in Fig. 4) has proved of immense value in research on the atom and sub-atomic particles, since many of these particles cause ionization of atoms in their movement through the atmosphere. Condensation immediately occurs along the path of the ions and reveals the actual track of the particle, which may be seen or photographed. There is no book on the electron published in the past twenty years or so without at least one illustration of a cloud-chamber photograph.

In his experiment Thomson irradiated air until the ionization was constant, and the magnitude of the total charge was measured by conductivity experiments. Then the cloud was formed, and the size of the individual drops in it determined. (In the previous year Townsend had shown how this could be done by regarding the minute drops falling through air as behaving like steel balls falling through a viscous liquid such as glycerine.) The rate of fall of the cloud was measured, the base being quite clearly defined. The total mass of water in the cloud was estimated by weighing, and hence it was possible to determine the total number of drops and thus of ions. Therefore, by utilization of the information concerning the total charge, the average charge (e) on a single ion followed immediately.

When the value of e was inserted in the value for $\frac{e}{m}$ it was found that m had a magnitude of only $\frac{1}{1840}$ of the mass of the hydrogen atom, the lightest known. So there was seen to exist a particle smaller than an atom. Many confirmatory experiments of increasing accuracy (R. A. Millikan's, for example) established the identity of this primary particle beyond question. It was the electron, the unit of electricity, negatively charged. The process of ionization was soon

seen to be the ejection of electrons from atoms, and the parent bodies were thus left *positively* charged, all normal atoms being electrically neutral.

Radioactivity

A phenomenon apparently of the utmost triviality was observed by Henri Becquerel in 1895. One of the properties of X-rays which attracted considerable attention immediately after their first discovery was the curious greenish fluorescence which was induced in the glass wall of the tube by the passage of X-rays through them. It is now known that this is of no great significance, but it prompted Becquerel to search for substances which behaved similarly in the natural state; his search was successful, for he found that uranium compounds produced this fluorescence, and further tests showed that they had the power of fogging photographic plates wrapped up in black paper. This pointed to the existence of a penetrating radiation. From his observation arose the whole science of radioactivity, which in our own time has culminated in an achievement more important than even a world war. In this study one name stands preeminent: that of Ernest Rutherford. Nearly all the significant advances in our knowledge of the atom attained during the first quarter of this century were to be associated with the scientist who has fitly been described as "the Prince of Investigators."

The chief source of uranium is pitchblende, a mineral consisting largely of uranium oxide, U_3O_8. Pierre and Marie Curie noticed from measurements of its ionizing intensity that it was more active than was to be expected from the amount of uranium in it. They therefore subjected it to a chemical analysis to determine what other constituents were present. As a consequence they discovered the two new

elements polonium (named in honour of Poland, Mme Curie's native land) and radium. Both of these elements were found to be radioactive; and not merely did they emit radiations which, like X-rays, could penetrate lead and then affect a photographic plate, but also, again like X-rays, they were capable of ionizing gases to a quite remarkable degree. The element radium was present in the pitchblende to the extent only of one part in three million of uranium, yet its tremendous activity made it readily detectable in such small amounts.

Nature of the Rays

Many discoveries of the highest significance followed one another in rapid succession. Rutherford soon reported that radioactive substances produced at least two sorts of rays, which he called α (alpha) and β (beta). The former were most intense near the specimen, but were absorbed by a few centimetres of air. The beta rays were much more penetrating, although the actual extent of their penetration could not be estimated, for they did not give straight-line paths. The immense usefulness of the cloud chamber was soon apparent for demonstrating the tracks of these particles. A third type of radiation, γ (gamma) rays, was discovered in 1900.

A thickness of gold leaf was found sufficient to absorb alpha rays, and it was then possible to examine beta and gamma radiation apart from the alpha constituent. Experiments with electric and magnetic fields showed that gamma rays were undeflected; they were later found to be similar to X-rays—that is, purely electromagnetic in nature. The beta rays were deflected in the same sense as electrons, and therefore possessed negative charges. Indeed, it was soon apparent from measurements of their charge and mass that

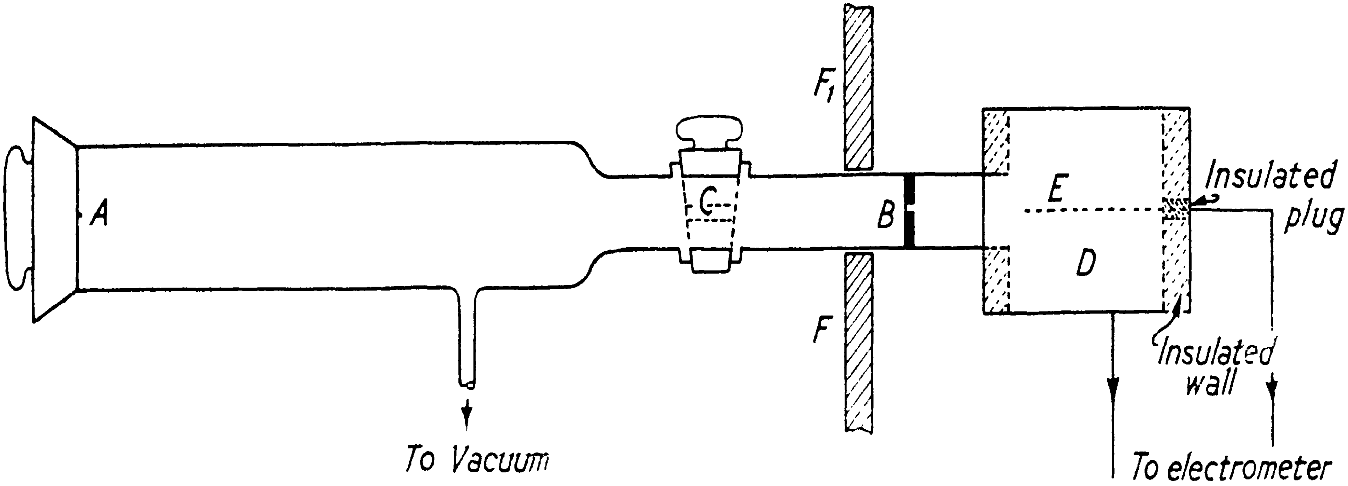


FIG. 5. COUNTING ALPHA PARTICLES

Alpha particles from the point source, *A*, pass through the open tap at *C* and through the narrow gap at *B*, which contains also a thin mica window to prevent the low-pressure gas in the Geiger counter, *D*, from escaping. The wire *E* is negatively charged, and the entry of an alpha particle causes ionization of the gas, whereupon an electric discharge passes between *E* and the wall. This is registered on an electrometer. *F* and F_1 are screens.

they *were* electrons. Finally the alpha rays were identified by Rutherford as ionized helium atoms.

The determination of the charge on the alpha particle was effected by first determining the total quantity of charge emitted in a given time from a sample of the radio-element and then counting the numbers of particles, so that simple division gave the required answer. Rutherford first measured the total quantity of positive electricity emitted by a point source of radium. To do this it was necessary to deflect magnetically the beta rays away from the receiver. Beta and alpha rays diverge in oppositive directions in a magnetic field, the former to a considerable extent compared with the latter. The apparatus was evacuated to prevent absorption of rays, the positive particles were collected on an insulated metal plate connected to an electrical measuring instrument, and the total quantity of electricity collected in a given time was measured.

To estimate the actual number of particles produced Rutherford and Geiger used an instrument which in its later, improved form is termed a Geiger-Müller counter.

Of the alpha particles radiated from the point source, *A* (Fig. 5), those which pass through the gap, *B*, enter the ionization chamber, *D*. A central wire is insulated from the wall of this chamber and connected to an electrometer (measuring instrument). The outer wall is connected to the positive terminal of a battery. Those alpha particles which enter the chamber. cause ionization (*i.e.*, removal of electrons) in the atoms of air present at low pressure, and a charge is communicated to the needle of the electrometer, which gives a kick. By a suitable choice of dimensions the number of particles entering the chamber can be regulated for purposes of counting.

From these experiments it was concluded that alpha particles carried a charge equal to twice the magnitude of but

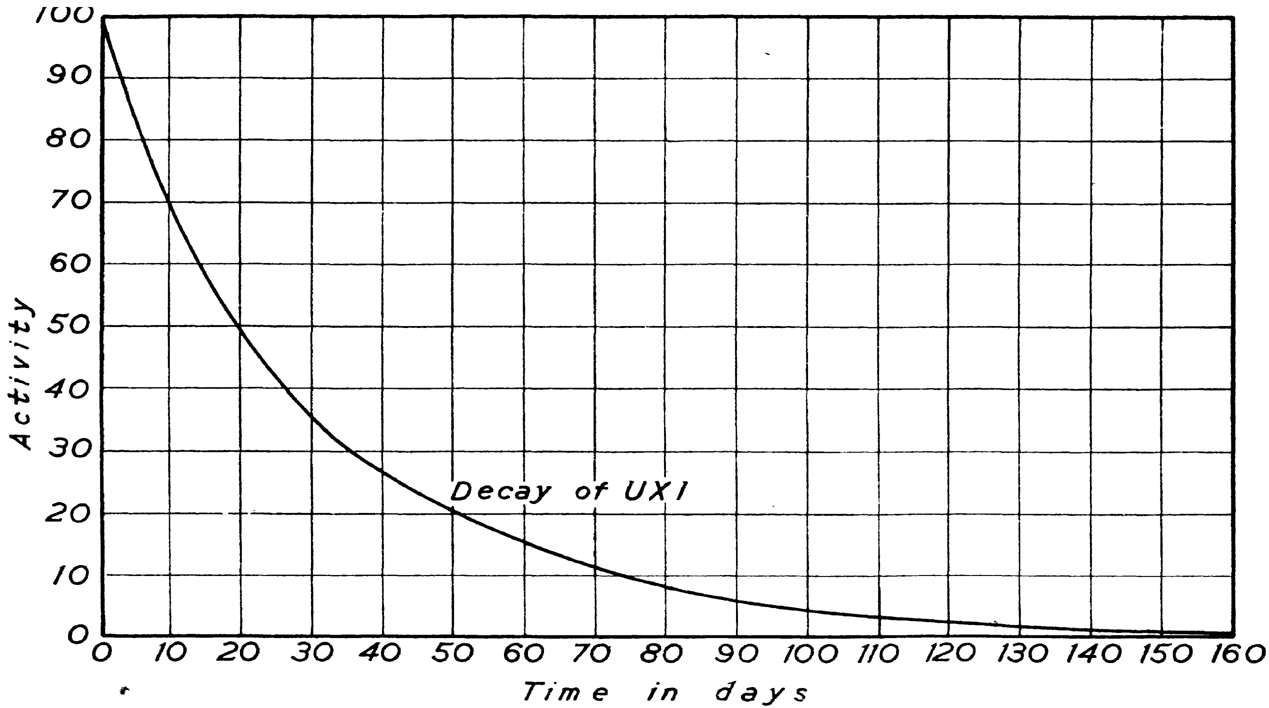


FIG. 6. THE DECAY OF RADIOACTIVITY

This curve is typical of the decline in activity of all radio-elements. For *UX* the activity after twenty days (approximately) is only 50, compared with 100 when first measured. After another twenty days it is about 25. The time for half-life varies widely from element to element, but is invariable for any particular element.

opposite in sign to that on, the beta ray or electron. This, taken in conjunction with the value of $\frac{e}{m}$ determined by deflection experiments, showed that the mass was approximately equal to four times the mass of the hydrogen atom. Later Rutherford and Royds enclosed the gas (radon) given off by radium—enclosed it in a glass tube whose walls were so thin as to enable the alpha particles to penetrate. They were collected in an evacuated tube for a period of days, and when subjected to an electric discharge gave the characteristic spectrum of helium.

A puzzling fact about radioactive preparations was that their activity diminished with time in an apparently capricious manner. After an immense amount of work, much of which is associated with the names of Rutherford and Soddy, the reason for this was made clear. It appeared that, starting with a chemically purified sample of the heaviest known element, uranium (atomic weight 238), a succession of other products, presumed elements, were formed in course of time, each in turn disintegrating to a lower member of the chain. The rate of formation of any substance from its parent depended on the amount of the parent substance actually present, so that the rate of decay of one substance determined the rate of build-up of the next. But even while this next was building up it was also decaying to a third substance at its own characteristic speed, which might differ widely from the characteristic speed of its predecessor. (Fig. 6 illustrates the decline in activity (ionizing power) of uranium X on being kept, uncomplicated by activity due to its products.) Furthermore, some of the substances formed were gaseous under normal conditions—such substances as radon and thoron—and their apparent changes in intensity, due to their being blown away by air currents, added to the immense complexity of the study.

Spontaneous Decay of the Elements

The radioactive constant which is used to designate each substance is the time necessary for the activity of a given radioactive body to fall to half its initial value. Thus it takes equal times for a body to fall successively to $\frac{1}{2}$, $\frac{1}{4}$, $\frac{1}{8}$ . . . of its original activity. (In short, the decay is exponential with time.) These half-life constants vary enormously. For uranium itself it is 5×10^9 years (five thousand million years), whereas for radium, a member of the uranium series of disintegration products, it is 1600 years. Thorium C_2, a member of the thorium radioactive chain, has a half-life value of only 10^{-11} second—one hundred thousand millionth of a second.

In 1903, as the result of extensive experience of these phenomena, Rutherford and Soddy put forward a theory of the spontaneous disintegration of the elements. According to this theory certain elements, notably those having atomic weights greater than lead, were in process of natural decay, and were giving off particles and being transformed into elements of lower atomic weight. No extremes of heat or cold affected this rate of decay, and there was a characteristic rate for each of the intermediate products in the chain of the decomposition. It is not to be wondered at that there was considerable opposition on the part of many scientists to this revolutionary theory, which appeared to strike at the very roots of chemistry and at conceptions which had proved their worth for a century. Nevertheless, inexorable fact demanded such an explanation, and before long it found general acceptance. In fact, chemistry proper was little affected by the changed views of the atom, for the great majority of the elements are apparently indefinitely stable and enduring. But the idea of an atom as an indivisible entity was banished for ever.

TABLE I

THE URANIUM SERIES OF RADIOACTIVE DECAY

ATOMIC WEIGHT	GROUP 0	1	2	3	4	5	6	7	8
238							Uranium U_1		
234					UX_1	UX_2	U_2		
230					Ionium				
226			Radium						
222	Radon								
218							Radium A		
214					RaB	RaC	RaC_1		
210				RaC_2	RaD	RaE	RaF (Polonium)		
206					RaG (Lead)				

II

THE STRUCTURE OF THE ATOM

The Conservation of Energy

The discovery that atoms contained particles of a more fundamental nature meant that atoms had some sort of 'structure'; the elucidation of this structure became henceforth the central objective of physics. At the same time scientists were becoming increasingly aware that the bedrock principles which had been accepted unquestioningly during the nineteenth century were in need of revision. Kelvin, doyen of British scientists, was not of this persuasion, however. He was particularly critical of the disintegration theory, for it implied an apparently ceaseless production of energy from nowhere. According to the Principle of Conservation of Energy, this very abstract thing called energy, which manifested itself either as heat (random motions of atoms) or as mechanical motion of gross objects, or in other ways, could be neither created nor destroyed. For example, when steam was utilized to perform some mechanical task, such as driving a train, it was well understood that its heat energy was transformed into an equivalent quantity of 'energy of motion' of the train, and that this motion was retransformed into frictional heat, equal in quantity to that given up by the steam. Initial heat had been degraded (*i.e.*, lowered in temperature), and was no longer available for doing work; but it had not been destroyed. This may be compared with water at a high level flowing through a sluice and harnessed to some mechanism before escaping to a lower level unchanged in quantity.

Nevertheless, Curie and Laborde had established by experiment the fact that heat was being generated continually by radioactive materials, which remained permanently at a temperature higher than their surroundings. According to measurements, radium generated enough heat to raise its own weight of water to boiling-point in one hour. The question arose, where did this heat come from? The answer was not to be found in the pages of classical physics, but was forthcoming from an apparently unrelated branch of science—the Theory of Relativity, propounded by Albert Einstein in 1905. While no pretence to do justice to this famous theory, even in a descriptive manner, will be made, it would be worth while briefly to outline the experiments which led up to its formulation, for the explanation it offers of the above-mentioned difficulty is an excellent illustration of the way in which a great scientific theory brings into one unified outlook the most diverse phenomena; and with the coming industrial exploitation of atomic energy one may realize, as has happened in the field of radio-physics, that the recondite theory of one generation provides the bread-and-butter occupations of the next.

Finite Velocity of Light

Nearly three hundred years ago the Danish astronomer Römer observed some rather puzzling behaviour on the part of one of the moons circulating round the planet Jupiter. He suggested as an explanation of the anomaly that light travels with a finite velocity, and deduced from his observations a value for this velocity not very different from the present accepted value. Subsequently other experimenters devised more accurate experiments to measure this property of light, of which that made by the French physicist Foucault is one of the best known, and is described in many books on

optics. The value of the speed of light at present accepted is 299,700 kilometres per second, more usually expressed in centimetres per second as approximately 3×10^{10}. Its symbol is *c*. *This speed is extremely high, but nevertheless finite, and this has led to the achievements (or troubles) of* relativity theory.

It is well known that the earth spins about its own axis once in about twenty-four hours, also that it describes an orbit round the sun once in 365 days. Further, the sun itself, together with its planetary system, is sweeping through the skies at a speed of about 18 miles per second relative to the average position of the 'fixed' stars, so that a point on the earth's surface is certainly moving at an appreciable, if unknown, speed through space. In the scheme of classical physics as laid down by Newton it is assumed that the heavenly bodies are set in an absolute space that exists quite independently of the bodies themselves. As a consequence every object must have some absolute velocity in this absolute space. In a celebrated experiment Michelson and Morley set out to determine the magnitude of the earth's absolute motion.

The Michelson-Morley Experiment

The lay-out of this experiment is shown in principle in Fig. 7. Light from a source (*A*) falls on the lightly silvered mirror (*B*), so that some is reflected along the direction *BC* to the mirror *C*, and some is transmitted to the mirror *D*, where the distance *BC* equals the distance *BD*. Reflection at both *C* and *D* occurs, the ray *CB* being partly transmitted through *B* to the telescope (*T*), and that from *D* being partly reflected along the same path (*BT*). Optical theory shows that, under these conditions, a beam of light originating from *A* will give interference fringes when viewed through

the telescope at *T*. These fringes consist of alternate dark and light bands, the dark bands occurring where the crest of one light wave just balances the trough of the other light wave, and the bright bands occurring where two crests, or

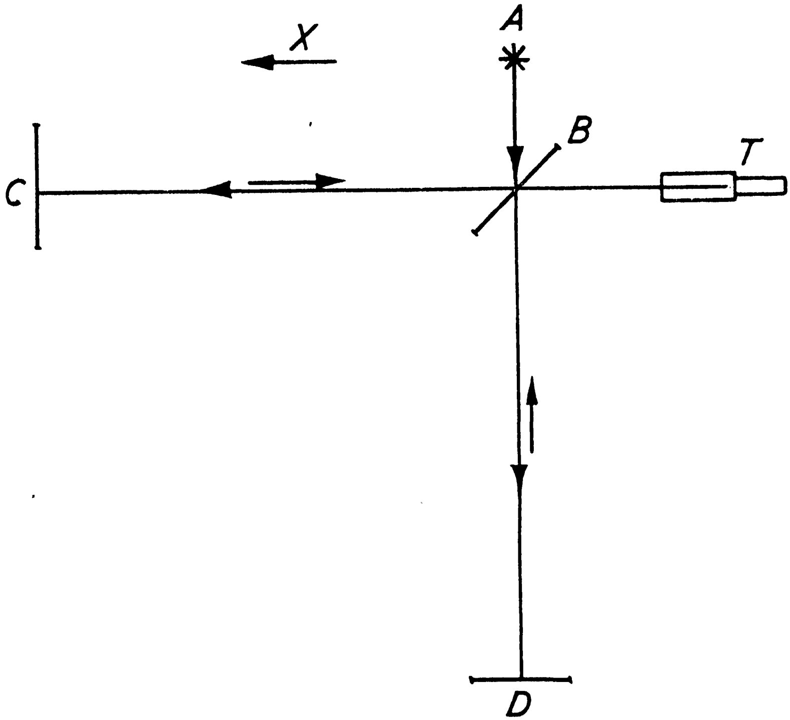


FIG. 7. THE MICHELSON-MORLEY EXPERIMENT
X shows the direction of the earth's rotation.

troughs, reinforce each other. The separation between dark and light bands will depend on the wavelength of the light used—that is to say, on its colour.

The apparatus is mounted so that the arm *BC* lies along the direction of the earth's rotation. Suppose the speed of rotation of the earth be v at its surface where the experiment is carried out: then one would expect that a ray of light coming from *B* in the same direction of motion as the earth

would have a velocity of $c + v$, in accordance with normal relative-velocity arguments. If the distance BC is a, then the time taken to travel from B to C will be:

$$t_1 = \frac{a}{c + v}.$$

On reflection at C the light will now travel against the motion of the earth, and the time taken will be:

$$t_2 = \frac{a}{c - v}.$$

The total time for this part of the journey will therefore be $t_1 + t_2$, which, after suitable algebra, $= \frac{2a}{c}\left(1 + \frac{v^2}{c^2}\right)$. Additional argument, not shown here, leads to an expression for the time of travel along BD and back, the ray travelling at right angles to the direction of motion of the earth. This expression is $\frac{2a}{c}\left(1 + \frac{v^2}{2c^2}\right)$. There is seen to be a small difference between these two values of time for the double traverse. Hence, if the whole apparatus is rotated through half a right angle, and the experiment repeated, a displacement of the interference fringes should be seen.

In actual fact no such displacement was found, although the method was sensitive enough to detect one-thousandth part of the expected difference. Scientists were slow in drawing extreme conclusions from this experiment, but eventually they were forced to adopt Einstein's viewpoint—that the velocity of light is constant to all observers, no matter what their motions relative to one another may be. In other words, if a velocity be added to or subtracted from the velocity of light the velocity remains just the same—namely, c. Thus the Michelson-Morley experiment might be carried out at a fixed spot on the earth's surface, and an

identical experiment observing the same source of light be carried out on a moving train, and the result would be the same. No correct determination of the velocity of light could give an answer different from any other, and it was therefore impossible for an observer to determine his motion relative to absolute space by noting his velocity relative to that of light moving without constraint in absolute space. Therefore, said Einstein, since absolute space and absolute motion (and therefore absolute time) are experimentally undetectable they have no physical meaning, and should not be used as a basis for the physical description of nature.

Einstein's Theory of Relativity

The apparent absurdity of adding or subtracting a finite velocity to or from the finite velocity of light and still getting the velocity of light was overcome by Einstein in what is known as the Special, or Restricted, Principle of Relativity. This principle virtually accepts the arbitration of experiment as final, and the 'special' theory recasts the dynamics of Newton to take into account the constancy of the velocity of light *in vacuo*.

For the addition of two velocities (u and v) in the same direction the resultant velocity (w) is given in relativity theory by:

$$w = \frac{u + v}{1 + \frac{uv}{c^2}}.$$

Now, since the everyday velocities of our experience are very small compared with the velocity of light (c), the expression $\frac{uv}{c^2}$ in the denominator of the above expression is usually vanishingly small, and the result is then practically:

$$w = u + v,$$

as in classical mechanics. It is otherwise when u and v are very large and of the same order of magnitude as c. The difference is then noticeable. Consider a ray of light coming from the sun and grazing the surface of the earth, which is rotating in a direction approaching the ray at 1040 m.p.h. (The circumference of the earth is 25,000 miles, and one complete rotation is performed every 24 hours.)

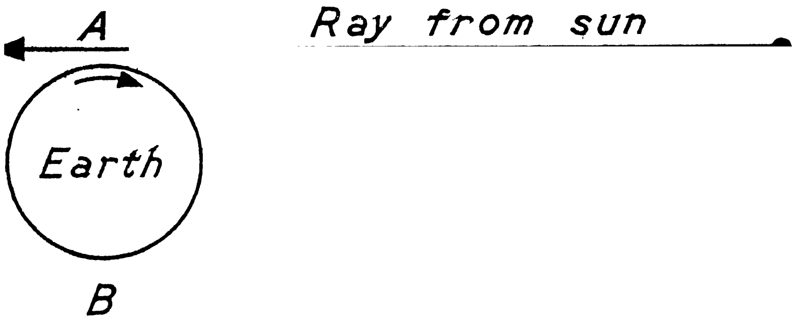


FIG. 8. THE RELATIVITY OF MOTION

According to Einstein the velocity of light measured by an observer at A is identical with that measured by an observer at B, although in the first instance the observer is moving towards the source and in the second away from it.

We must put $u = 1040$ miles per hour and $v = c$ miles per hour in our formula. Then the observed velocity will be:

$$w = \frac{u + v}{1 + \dfrac{uv}{c^2}} = \frac{1040 + c}{1 + \dfrac{1040c}{c^2}} = \frac{1040 + c}{1 + \dfrac{1040}{c}}.$$

Multiplying top and bottom of this last expression by c, we find:

$$\frac{c\,(1040 + c)}{c + 1040} = c,$$

so that the velocity of light from the sun as measured by an observer approaching the sun will be identical with that

measured between two stationary points in conformity with the Michelson-Morley evidence.

A number of significant conclusions follow from this line of reasoning. One is that as the velocity of a body increases so does its mass, and to impart to a body the velocity of light would make its mass virtually infinite. It would also require an infinite force to do so. Therefore, it is physically impossible for any material body to travel with this velocity c.

Another curious fact is that the energy of a body which on Newtonian (classical) mechanics is represented by half the product of the mass and the square of the velocity, *i.e.*,

$$E = \tfrac{1}{2}\, mv^2,$$

has a somewhat different formula in relativity theory owing to the change of mass with velocity. The relativity expression is:

$$E = \frac{m_0 c^2}{\sqrt{1 - v^2/c^2}},$$

where m_0 is the rest mass as measured by the observer and v is the velocity which the mass acquires relative to the observer. This expression, after suitable manipulation by means of the Binomial Theorem, becomes to a high approximation:

$$E = m_0c^2 + \tfrac{1}{2}\, m_0v^2.$$

Identity of Mass and Energy

The second term on the right is the energy given by classical physics, but the term m_0c^2, which according to relativity theory is just as much a part of the energy of the mass m_0, is not so given. What meaning, then, is to be given to the expression m_0c^2? Einstein suggested that this energy was the intrinsic energy of a particle, at rest relative to the observer, and was characteristic of the mass m_0. In other

words mass was energy (and energy mass), so that the energy stored in any mass m_0 grams was numerically equal to E ergs of energy where $E = m_0c^2$, c being measured in centimetres per second. (An erg is the amount of energy given by one gram weight falling through a distance of one centimetre, divided by the gravitational acceleration constant, $g = 981$.)

It has already been remarked that c has the numerical value of 3×10^{10} centimetres per second, so that $c^2 = 9 \times 10^{20}$, and therefore a mass of one gram weight ($m_0 = 1$) has an intrinsic energy E ergs $= 1 \times 9 \times 10^{20}$, or 900,000,000,000,000,000,000 ergs.

Another useful measure of energy is the calorie. This is the amount of heat (another form of energy) required to raise one gram of water one degree centigrade. There are $4{\cdot}2 \times 10^7$—*i.e.*, 42,000,000—ergs in a calorie. Therefore

$$1 \text{ gram weight} = \frac{9 \times 10^{20}}{4{\cdot}2 \times 10^7} = 2{\cdot}14 \times 10^{13} \text{ calories—}$$

i.e., about $21\frac{1}{2}$ million million calories. Hence the annihilation of one gram of matter (of any sort), were it possible, would liberate the above quantity of heat.

One ounce of any form of matter—say, coal—if annihilated would give 28·35 times the above quantity, because there are 28·35 grams in the ounce. This is 6×10^{14} calories, whereas the ordinary combustion of one ounce of coal gives just over 200,000 calories. Thus annihilation is three thousand million times more effective in energy production than is combustion.

After Einstein had dealt with the problem of bodies moving with constant speed relative to one another he extended his theory to consideration of accelerated motions. This extension is included in what is known as the General Theory of Relativity, published between 1915 and 1918.

Many unusual conclusions were reached, such as, for example, that a ray of light from a distant star is bent when passing the sun. These developments do not at present concern the Atomic Theory, although they are undoubtedly destined to do so in the future. Nevertheless the relationship $E = m_0c^2$ is fundamental for calculating all energy liberations in atomic disruptions, and has been checked by measuring energy released in cloud-chamber collisions with known mass losses. However, this topic will be returned to later.

As a result of the new physical outlook the ideas of fixity in mass and energy expressed in the nineteenth-century principles of Conservation of Energy and Conservation of Mass are abandoned, and instead a single principle, the Conservation of Mass-energy, replaces them. For mass and energy now appear as dual aspects of a single concept, which, for want of a better term, is called mass-energy. It can be understood from these ideas that the heat liberated by radioactive elements is obtained from mass conversion, although the enormous ratio of equivalence between mass and energy ensures an apparently inexhaustible supply of heat from this source.

Even in ordinary chemical reactions, such as the combustion of petrol, the heat liberated is responsible for a minute and quite unweighable loss in weight. In Lavoisier's experiment his mercury oxide weighed an infinitesimal fraction less than the weight of the mercury and oxygen separately, for a certain amount of heat was released in its production —but not enough to weigh on the most sensitive microbalance ever invented.

The attainment of mechanical velocities approaching that of light is rare in our experience, but instances are known. The beta rays from radium are ejected with 99 per cent. of that velocity, and here the relativity correction due to in-

crease in mass is perceptible, and must be allowed for in calculations.

Except in cases where high-energy concentrations are concerned—for example, of particles moving with nearly the speed of light—or questions concerning the nucleus of the atom, the results of relativity and classical dynamics are practically—that is, experimentally—indistinguishable. In the great majority of calculations there is, therefore, no need to adopt the refinements of relativity theory.

Quantum Theory

We have seen that the theory of relativity grew out of the experimental fact that velocities greater than that of light are unobservable. Nevertheless, the new ideas were a natural outcome of the mechanics of Newton, with the above-mentioned limitation superimposed. They were not in spirit contradictory to the old outlook, and, as we have seen, relativity mechanics reduces to classical mechanics for velocities of ordinary experience.

But the beginning of this century saw also the birth of another theory which made a complete break with accepted ideas, and, in many ways, even to-day seems contrary to reason. In 1901 Professor Max Planck, of Berlin, enunciated the Quantum Theory, in a successful attempt to interpret difficulties which had arisen in the study of radiation. It was realized at the time that Maxwell's Equations of the Electromagnetic Field governed the behaviour of radiation of all kinds—light, radiant heat, and the then recently discovered radio waves which were engaging the attention of many physicists.

From the basic equations of Maxwell could be derived a so-called second-order equation, which, by its mathematical similarity to the equations for the propagation of waves,

suggested that electromagnetic disturbances were propagated through space with a wave-motion in all directions.

On applying these ideas to the consideration of absorption and emission of heat radiation Rayleigh and Jeans (1900) obtained a formula which fitted the experimental results quite well for long wavelengths, but not for short. W. Wien, on the other hand, had obtained a formula which gave good results for short wavelengths—that is, high frequencies—but failed where the Rayleigh-Jeans Law was successful.

Planck abandoned the idea of continuity, which is characteristic of wave-motion, and assumed that the energy in the radiation was absorbed or emitted in pulses and depended on the 'frequency' of the waves—*i.e.*, the number of times per second that a crest is reached.

Wavelength and frequency are simply related to the velocity of propagation of the wave by the relationship:

$$\underset{\substack{\lambda \\ \text{(lambda)}}}{\text{wavelength}} \times \underset{\substack{\nu \\ \text{(nu)}}}{\text{frequency}} = \underset{(c)}{\text{velocity}}.$$

Planck's theory is summed up in the equation:

$$\underset{\text{energy of radiation}}{E} = \underset{\text{Planck's constant}}{h} \times \underset{\text{frequency}}{\nu}.$$

Planck's constant has the physical dimensions of energy $\times$ time, or action, and the numerical value of $6{\cdot}55 \times 10^{-27}$ erg second.

Einstein extended Planck's conception of a discontinuous radiation process to the idea that radiation itself was discontinuous, and was propagated discontinuously as packets, or 'photons.'

Despite some successes the real adoption of the Quantum Theory did not take place until Niels Bohr (1912) utilized it to explain the functioning of sub-atomic processes. In order to follow this application it is now time to return to

the consideration of the experimental evidence on the structure of the atom which had accumulated by 1912.

The Scattering of Alpha Particles

In 1906 Rutherford was studying the deflection of alpha particles by a magnetic field, when he noticed that some of them were scattered by residual air in his vacuum tube. He pursued this observation by studying the scattering of the particles in a thin sheet of mica, about one-thousandth of an inch thick. The scattering effect was observed visually by allowing the alpha particles to fall on a zinc-sulphide screen, which was examined under a microscope. Crookes had discovered earlier that such a screen gave a visible flash when struck by these particles. Rutherford found that some of the particles were deflected about two degrees from their course. He calculated that to suffer such a deflection they must have been subjected to an average electric field of one hundred million volts per centimetre.

Geiger and Marsden continued this investigation, and soon found that an occasional particle—one in twenty thousand or so—was deflected sufficiently to emerge from the foil on the same side as it had entered. On the basis of such results Rutherford concluded that the atom contained within it a centre of intense electric force. Now for a given electric charge on a sphere the 'potential' (voltage) increases as the radius of the sphere is reduced; and on this basis, knowing the energy of the impacting alpha particle and the law governing the repulsion of two like charges (Coulomb's Law of Inverse Squares), he was able to calculate the dimensions of the positive atomic charge, and to show that the number of positive charges (hydrogen having one) was roughly half the atomic weight of the element.

His calculations showed that the positive charge was

centred on a particle, or 'nucleus,' about one million millionth of a centimetre in diameter (10^{-12} cm.), whereas the diameter of the atom was of the order 10^{-8} cm.—*i.e.*, one hundred millionth of a centimetre—so that the nucleus was only one ten thousandth (10^{-4}) of the diameter of the whole atom, and hence 10^{-12} of the volume.

The nucleus is therefore of similar size to the electron. Further, since measurement had shown that the mass of the electron was negligible compared with that of the positively charged particle, it seemed likely that almost the whole mass of the atom was situated in the minute nucleus, which therefore must have a density of at least a million million times that of ordinary solid matter.

The Rutherford-Bohr Atom

Rutherford, on the basis of these scattering experiments, enunciated his Nuclear Theory of the Atom. According to his theory the atom consisted of a minute nucleus positively charged and containing virtually all the mass of the atom, surrounded by planetary electrons equal and opposite in charge to the number of positive charges in the nucleus. Hence the normal atom was electrically neutral. The hydrogen atom consisted of a nucleus, the proton, having unit mass and a single positive charge, surrounded at a distance of roughly one hundred thousand times its nuclear diameter by a single electron revolving round it, as a planet revolves round the sun.

There were very grave objections to this model of the atom. In the first place, according to classical electrodynamics an electron moving in such a path must radiate energy, whereas normal atoms do not do so. In the second place, such an atom could not be stable, for the electrons would describe decreasing circles and eventually collapse on

to the nucleus. Nevertheless, the model was consistent with Rutherford's facts, and also explained the penetrating effects of the sub-atomic particles—for it was apparent that on this theory most of the atom is empty space.

It was to this model of the atom that Bohr applied Planck's Quantum Hypothesis, suitably modified, and in so doing opened up atomic processes to mathematical calculation, at the same time securing the greatest triumph for the Quantum Theory itself.

Bohr postulated that, contrary to classical ideas, an electron could move in a closed orbit without radiating energy. Secondly, he showed that many such orbits were possible, and that when an electron moved from one orbit to another it did so not in a spiral but in a single jump. These non-radiating orbits he called stationary states, and a jump from one stationary state, or energy level, to another was accompanied by the emission or absorption of a quantum of radiation. The actual dimensions of these possible stationary orbits were governed by the quantum condition that the 'angular momentum'—that is, the product of the mass of electron (m), its peripheral velocity (v), and the radius of the orbit (r)—was an integral multiple of $\frac{h}{2\pi}$. Thus:

$$m\,v\,r = \frac{n\,h}{2\pi},$$

where n is an integer 1, 2, 3 . . . , and h, as before, Planck's constant of action. If E_1 is the energy of an electron in one stationary state and the electron jumps to another orbit of energy E_2, then, according to Bohr, the frequency of the emitted radiation ν (nu) is given by:

$$E_1 - E_2 = h\,\nu.$$

It will be apparent from these ideas that energy emission from the Rutherford-Bohr model atom should occur in

discrete quantities at definite frequencies. This is precisely what is known to happen in actual fact.

The Optical Spectrum

To show this it will first be necessary to refer to the subject of spectroscopy. Newton discovered that when ordinary white light is passed through a slit and then through a glass prism it is split up into a spectrum, a series of colours stretching from violet at one end, through blue, green, and yellow, to red at the other end. Nearly two centuries afterwards Fraunhofer found that this spectrum (of which the rainbow is an example) is crossed with innumerable fine dark lines, each the image of the slit through which the light has emerged. These Fraunhofer lines in the sun were investigated extensively by various physicists, who were able to reproduce their pattern in the laboratory. Thus, if a little common salt is put into a non-luminous flame a yellow light is immediately visible to the eye, and if this light is examined through the spectroscope there will be seen a very simple spectrum—namely, two yellow lines close together, called the D_1 and D_2 lines of sodium. These lines are characteristic of any compound containing sodium, such as sodium chloride (common salt). Similarly, other elements are characterized by their own, usually more complex, spectra. Hydrogen (as the simplest element) has a spectrum of especial interest, and Balmer succeeded in discovering a simple empirical formula which enabled its lines to be calculated. But there was no explanation forthcoming as to how they originated; it was surmised that some very complex vibrations were taking place in the atom, of which the spectral lines were the result.

Bohr was able to calculate the exact position of the spectral lines of hydrogen by means of his theory, utilizing

known information such as the mass and charge of the nucleus and the value of *h* deduced by Planck. He predicted not only the lines in the visible part of the spectrum, but those in the ultra-violet and infra-red as well.

Later Bohr extended his calculations to explain the spectrum of ionized helium. The nucleus of this atom consists of a mass of approximately four units carrying two positive charges, and in the normal atom there are two electrons circulating well away from the nucleus. If, for any reason, an electron has been removed from the atom the latter is said to be (singly) ionized. (When doubly ionized it is an alpha particle.) Apart from mass-and-charge difference, the mechanics of the ionized helium atom are plainly similar to those of the hydrogen atom. Bohr calculated this spectrum, and physicists were able to confirm it in the laboratory. They also recognized the lines, in the exact position calculated, in the light from the sun, thus demonstrating the presence of helium in the sun's atmosphere.

Bohr's ideas provided the key to the interpretation of spectra generally, of both atoms and molecules—the latter give what are known as 'band spectra.'

To-day spectroscopy is a vast subject, dominated entirely by quantum principles. By the use of modern apparatus measurements of extreme refinement are possible, and much of our information about atomic processes is obtained from this source.

The Nature of X-rays

It is now advantageous to note the progress made in the study of X-rays, whose discovery was described in the first chapter. For a number of years after their discovery there was much controversy as to whether they were particles, like the electron, or electromagnetic waves, similar to light. Much evidence accumulated to show that they were similar

to light waves, and by 1911 their wavelike nature was generally accepted. In that year Barkla made the important discovery of their characteristic radiation. He showed that if a beam of X-rays, reflected from the target of an X-ray tube, is allowed to fall on a second substance, secondary rays are emitted from this latter target, characteristic of the elements present there. These rays consist, for a single atomic species, of two groups, one of which has a greater penetrating power than the other. The more penetrating (harder) rays were designated K-radiation and the less L-radiation. The radiations, both K and L, became harder as the atomic weight of the element in the second target increased.

Diffraction of X-rays

The year following a still more important discovery was made—the diffraction of X-rays. Ordinary light, it had long been known, when allowed to impinge on a surface containing parallel lines ruled very close together, was 'diffracted,' giving a system of alternate light and dark bands. From the dimensions of the grating, as this ruled surface is called, it was possible to calculate the wavelength of the light used.

X-rays had not been studied in this manner, for it had not been found possible to rule a diffraction grating with lines sufficiently close together to deal with the very short wavelengths concerned. But in 1912 von Laue suggested that the crystalline structure of minerals was due to a regular packing of atoms forming a natural three-dimensional lattice, and that such a space lattice might serve as a diffraction grating. Friedrich and Knipping tested the hypothesis and confirmed that this was indeed so. They passed a beam of X-rays through a zinc-blende crystal and photographed the resulting radiation. A series of regularly arranged spots was obtained, which indicated a diffraction effect. The reason

crystals act as diffraction gratings is that the atoms in them are arranged regularly at distances of about one hundred millionth of a centimetre apart, which is of the order of the X-ray wavelengths. This discovery not only made possible the analysis of X-rays, but also provided a means of investigating crystal structure. The theory of X-ray diffraction was propounded by Sir William Lawrence Bragg, who, with his father, the late Sir William Henry Bragg, made extensive investigation in X-ray crystallography.

The Atomic Number

Shortly afterwards (in 1913) H. G. J. Moseley applied the diffraction technique to a study of the characteristic radiation of the elements, with most significant results. He used a target of the element under investigation, and diffracted the rays from a crystal of potassium ferrocyanide. The diffracted beam was then photographed. By the method just outlined it was possible, from the position of the lines in the resultant spectrum, to determine their frequency, and by comparing together the spectra of several elements (Fig. 9) he saw that for a particular type of radiation the lines changed regularly from element to element. (X-ray spectra are simple, compared with optical spectra, and this facilitates examination of particular lines or groups of lines.) Now Moseley found a very interesting relationship between the frequency, ν (nu), of a particular line and the position, N, of the element in the atomic-weight series. The results could be expressed:

$$\nu = a\,(N-b)^2.$$

a and b were constants—*i.e.*, had simple arithmetical values for particular sets of lines. Thus b was constant for all the hard (K) radiation of all the elements examined and was almost exactly 1, whereas a was constant for all the

Kα lines, the strongest lines in the K group; but, most important of all, N was an integer rising in value from 1 for hydrogen to 92 for uranium, the highest value encountered in nature. Thus N increased as the atomic weight increased, and the elements could be arranged in the Periodic Table with atomic number instead of atomic weight as the criterion of elemental nature. When this was done it was found that the order of the elements was identical with the atomic-weight order, with three exceptions. Three pairs of elements—namely, argon and potassium, cobalt and nickel, and iodine and tellurium—just did not fit into Mendeleev's table when inserted according to their atomic weights, but had to be reversed in order to do so. Argon is a chemically inert gas, and plainly belongs to the column which includes the other inert gases, such as helium and neon—namely, group O—but it has an atomic weight of 39·94, which is higher than that of potassium (39·09), a strongly reactive alkali metal, chemically similar to sodium and lithium. It was necessary to insert them in the table in reverse order of their atomic

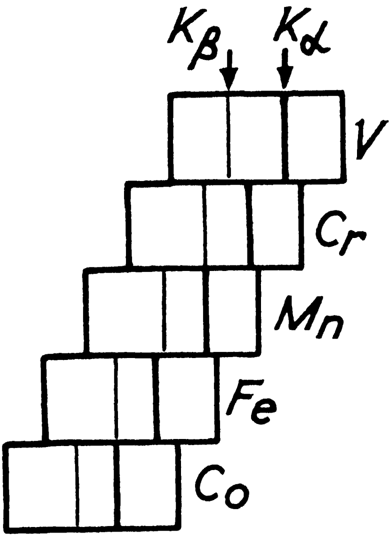


FIG. 9. X-RAY SPECTRA OF THE ELEMENTS

When the characteristic X-ray spectra of the elements are put side by side and compared there is seen to be a step-wise displacement of the $K\alpha$ (heavy) line and similarly of the $K\beta$ (faint) line. Moseley's formula for these lines contains a number, N, which, when increased by unity successively, gives the characteristic lines of all the elements from hydrogen to uranium.

weights, for their chemical behaviour demanded it. But the atomic number justifies this reversal, argon being 18 and potassium 19. Thus the atomic number seems a more fundamental property than atomic weight. The reason for the above anomalies was soon to be made clear, however.

Moseley concluded that the number *N* was a property of the nucleus, for, in accordance with the Bohr theory of the Rutherford atom, the frequency of radiation would depend on the nuclear charge. *N* was therefore considered to be the net positive charge carried by the nucleus. Since the atom is normally electrically neutral there must therefore be *N* electrons circulating round this nucleus. It is now known that these electrons—or rather the outer fringe of them, which are most readily detachable—account for all the chemical properties of the element.

Isotopes: the Group Displacement Law

The tale of discovery in the two or three years prior to 1914 is by no means exhausted yet, and we must now revert once more to the subject of radioactivity. There had accumulated by 1911 so many radioactive substances with characteristic decay constants that there was just no room for them in the Periodic Table, and they were becoming increasingly difficult to classify. In that year Frederick Soddy made a notable advance by suggesting that those elements which lost an alpha particle became displaced in the Periodic Table two places to the left, and thence became akin to the element in the new place. In 1913 he, and others, added the suggestion that expulsion of a beta ray (electron) displaced the radio-element one place to the right in the Periodic Table. This generalization of displacement for alpha and beta particles is now known as the Group Displacement Law. Soddy also recognized that substances of different atomic

weights might occupy the same place in the table, but that elemental identity would be indicated by the possession of the same atomic number. Such substances he called 'isotopes' (Greek, 'equal place'). In the light of this law it is now possible to understand the complex changes which take place in radioactive transformations. First it should be recalled that the alpha particle is a helium atom of mass 4 units, which has lost two practically mass-less particles of negative electricity. The helium atom is the second lightest element known, and has an atomic number of 2—*i.e.*, two positive charges in the nucleus. Therefore loss of an alpha particle will result in a reduction of 2 in the atomic number (total nuclear positive charge) and a reduction of 4 in the mass.

Now uranium has an atomic weight of 238 and atomic number of 92. It loses an alpha particle and becomes an element of atomic weight 234 and atomic number 90 called UX_1. Next, UX_1 emits an electron from the nucleus. The loss of a negative charge by the nucleus is equivalent to the gaining of a positive charge, so that the atomic number jumps up to 91. The mass of an electron, however, being only $\frac{1}{1840}$ of a proton, may be ignored, and therefore the atomic weight remains at 234. This is the element styled UX_2 in the table. UX_2 is also beta radioactive, with the result that the atomic number jumps back to 92 again, but the mass remains at 234. The element having the same number as the initial uranium, but a mass of 234 instead of 238, is therefore an isotope of uranium and styled U_2. It is present to the extent of only 0·008 per cent. in ordinary uranium minerals, and therefore does not perceptibly influence the atomic-weight determination. U_2 next emits an alpha particle and becomes ionium, atomic number 90 and atomic weight 230—an isotope, therefore, of UX_1. Ionium emits a further alpha particle and becomes an element of

atomic number 88 and atomic weight 226. This is radium, and occupies the same column (not the same place in the column) as barium and strontium, with which it is chemically allied. After a number of such changes the series finally becomes stable with radium G, which has an atomic number of 82 and an atomic weight of 206. But lead also has an atomic number of 82, and therefore lead and radium G are isotopes. Two other radioactive series—the thorium series and the actinium series—also terminate in elements of atomic number 82. In the former instance, however, the atomic weight is 208, and in the latter 207. These two are isotopes of lead, whose atomic weight, determined by ordinary chemical means, is 207·2.

A reason is now apparent for such fractional atomic weights: they are merely the averages of whole numbers which are the atomic weights of various isotopes present in different proportions. Strength is lent to this interpretation by the fact that uranium and thorium minerals are inevitably found in nature associated with lead, and the atomic weights of the various samples of lead are quite definitely different, in accordance with their mode of origin just outlined.

It must not be supposed that the idea of 'mixed' elements was accepted quite so easily as the above account suggests, for atomic weight had been recognized for more than a century as the criterion of elemental individuality. The most accurate experiments of innumerable chemists the world over had established the fact that the atomic weight of each of the elements, with perhaps one exception, was an invariable property of the particular element, no matter what the source from which the sample was taken. The one exception was lead, which certainly showed small but unaccountable variations according to the origin of the sample. As for the radioactive elements, most of the evidence for their

existence and most of the information about their properties was physical rather than chemical; they existed in minute amounts, and their life was undoubtedly transitory. Much more conclusive evidence was needed before such an abrupt break with tradition would be accepted. This was soon to be supplied.

Positive Rays

Mention has already been made of the fact that an atom which has lost one electron becomes 'ionized,' and is no longer electrically neutral but positively charged. As early

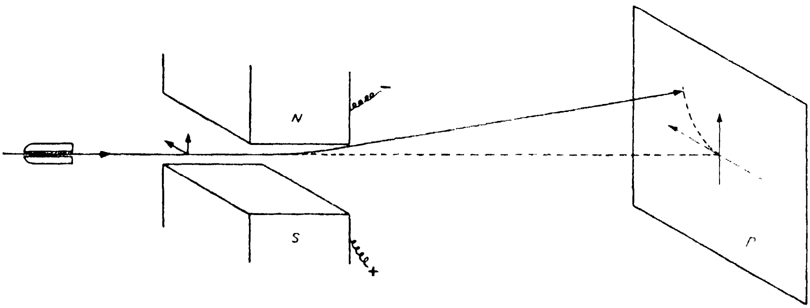


FIG. 10. THOMSON'S POSITIVE-RAY ANALYSIS

A positively charged particle, on passing through the space between the magnets, is acted on by two influences: one, shown by the upward arrow, caused by electric attraction, and the other, shown by the sideways arrow, caused by the magnetic field. The particle swerves out of its straight-line path as a consequence and lands on the plate *P* remote from the undiverged rays. Other particles of the same kind, but with differing velocities, will all lie on the curve (parabola) shown.

as 1886 Goldstein had bored holes in the cathode of his discharge-tube and found that rays streamed through these holes in the opposite direction to the rays (electrons) which left the cathode for the anode. By 1912 Sir J. J. Thomson had succeeded in overcoming the many technical difficulties associated with the investigation of these 'positive rays,'

and was able to analyse a stream of them by means of crossed electric and magnetic fields applied simultaneously, as in his earlier investigation of e/m for the electron. (A schematic outline of the apparatus is shown in Fig. 10.) When using neon Thomson found that there were two distinct parabolas, suggesting two ingredients of what had been considered an element. In 1913 F. W. Aston took a sample of neon and diffused it through a porous pipeclay surface. After repeated diffusions he was actually able to separate the gas into two fractions of slightly different density.

The Mass Spectrograph

In 1918 Aston returned to the study of positive rays, and constructed a modified apparatus in which the electric and magnetic fields were applied successively. He utilized the

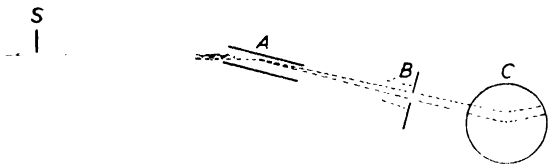


FIG. 11. SCHEME OF ASTON'S MASS SPECTROGRAPH

Positive ions pass through the slit *S* as a narrow beam, and are diverged according to their mass and velocity by the pair of electrically charged plates, *A*. A portion of this beam, in which all particles having the same charge will also be travelling with roughly the same velocity, is selected by the slit *B*. This beam passes across the poles of a powerful electromagnet, *C*, which converges all particles of the same charge (already moving with the same velocity) to a point on the photographic plate, *P*.

magnetic field to bend back the rays which had been deflected by the electric field. As a consequence he was able to focus all rays of a given mass, no matter what their velocity, on to a single spot, instead of spreading them out over a curve. This, and various other refinements, improved

sensitivity and enabled results of high precision to be obtained. He called his apparatus the 'mass spectrograph,' because masses were focused to form a spectrum, and the various masses corresponding to isotopic constituents were distributed at intervals in a straight line. The basic outlines of the method are shown in Fig. 11. Results of the most outstanding importance were obtained by Aston with this, and later with an improved mass spectrograph.

Within a few weeks of commencing operation mass-spectra photographs were obtained which proved conclusively that two fractions of neon were always present in any given sample of the element, and that these two fractions had whole-number atomic weights of 20 and 22. The mass 20 was present in much greater abundance than 22, and later measurement of the intensities of the two spots indicated that the relative proportions were such as to give a mean atomic weight of 20·2, the accepted chemical atomic weight. Later, a minute trace corresponding to a mass of 21 was confirmed.

The element chlorine, with a chemical atomic weight of 35·5, was found to give four fractions corresponding to masses of 35, 36, 37, and 38, of which 35 and 37 were by far the most abundant. Later it was proved that the masses 36 and 38 were due to hydrogen chloride (HCl) molecules, which, of course, would have a mass corresponding to the sum of the masses of the individual atoms.

The reason for the reversal of argon and potassium in the atomic-weight order was also made clear. Argon, with atomic number 18, has two isotopes of masses 36 and 40, of which 40 is the more abundant. The net effect is to bring the atomic-weight determination of this element up to 39·94. Potassium (atomic number 19) has isotopes 39 and 41, but it is the ligher isotope which this time is much more abundant, so that the mean atomic weight is 39·09. Normally the

relative abundances of the various isotopes is such as to ensure that the mean atomic weights of the elements follow in the same order of magnitude as their atomic numbers, but in the case of the three pairs of 'anomalous' elements mentioned earlier this is not so.

The Whole-number Rule

In the course of time all elements were examined for isotopic constituents, but long before then Aston had been able to announce an important generalization—that to a high degree of accuracy the weights of all atoms could be expressed as whole numbers. This is known as the Whole-number Rule. They were whole numbers, that is to say, provided oxygen were taken as a standard of comparison with the value of 16·000. On this oxygen scale the only element which did not obey the rule was hydrogen, whose atomic mass was 1·008, but the exception was expected. For if, as appeared likely from these results, Prout's Hypothesis concerning the building up of all the elements from hydrogen—'protyle'—were after all true, then it was understandable that such a condensed system of protons (hydrogen nuclei) would be stable only if energy were given out in the process of condensation. But loss of energy would result in loss of mass, as we have seen from relativity theory. Thus the condensation of sixteen gram-atoms (atomic weight expressed in grams) of hydrogen to form one gram-atom of oxygen of mass 16·000 should result in the liberation of:

$$16 \times 1{\cdot}008 - 16{\cdot}000 = 0{\cdot}128 \text{ gram.}$$

From Einstein's equation:

$$E = 0{\cdot}128 \times (3 \times 10^{10})^2 \text{ ergs is liberated.}$$

This is $1{\cdot}15 \times 10^{20}$ ergs, or two and three-quarter million million calories. Similarly, this quantity of energy would

need to be added to disrupt 16 grams of oxygen into primary particles. It would seem from the Whole-number Rule that all the elements are constructed after the same style as oxygen, and were formed with liberation of roughly the same amount of mass-loss per proton.

Packing Fractions

Although this rule is very nearly exact, there were, Aston saw, some very slight deviations from whole numbers, and to investigate the magnitude of these deviations—which, of course, were important from the point of view of the energy of binding of the particles in the nucleus—he constructed a second mass spectrograph in 1924. This second instrument gave an accuracy of mass determination of one part in ten thousand. Again some most important results were obtained. The small deviations were expressed as a percentage of the whole numbers, and the fractions—called 'packing fractions'—for the various elements were plotted as a graph. The result was a continuous curve, shown in Fig. 12. The packing fraction for oxygen was taken as an arbitrary zero, and on this scale, of course, hydrogen had a positive packing fraction of

$$\frac{1{\cdot}008 - 1{\cdot}000}{1{\cdot}000} = 0{\cdot}008, \text{ or } 0{\cdot}8 \text{ per cent.}$$

This figure is shown as 80 on the graph. The curve descends steeply from hydrogen to oxygen, with a small branch containing helium and carbon, having much smaller values than lithium (Li), boron (B), and nitrogen (N). All these elements have lost less mass, and therefore energy, per proton used in their construction than has oxygen. The curve then descends below zero for all those elements even more firmly bound than oxygen, and eventually bends up, until at

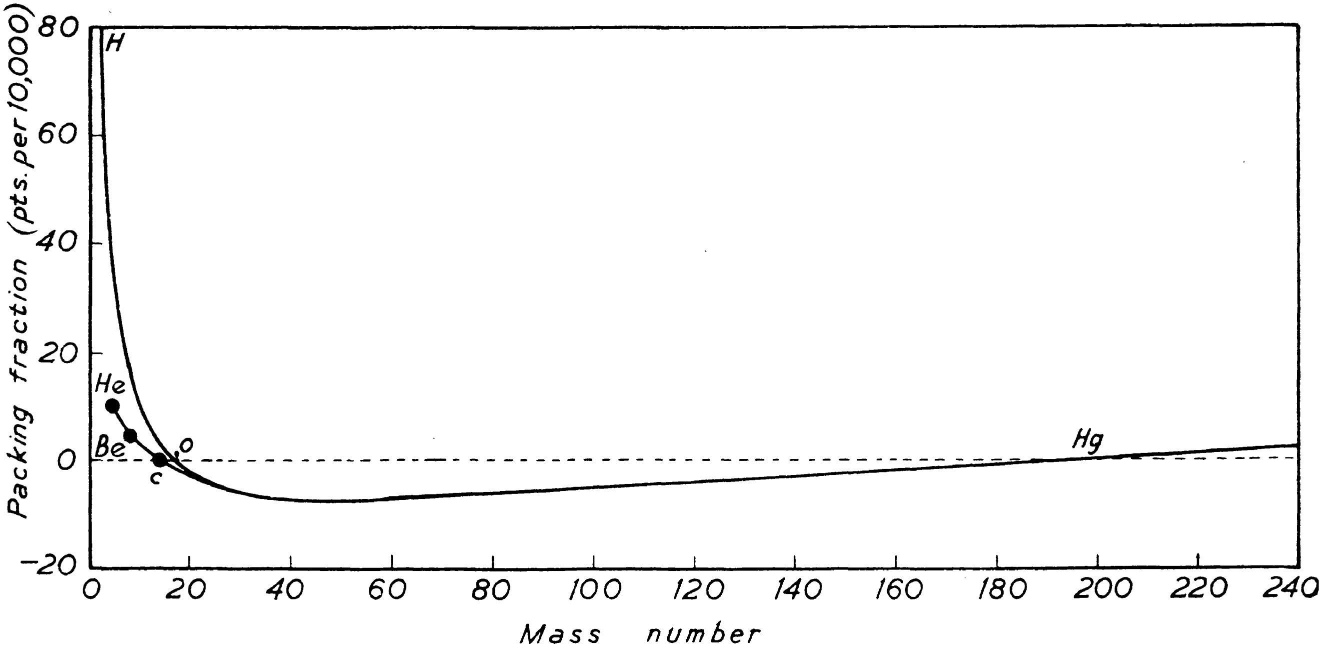


FIG. 12. PACKING FRACTIONS OF THE ELEMENTS

All elements below the dotted line—that is, with atomic weights between 16 and 200—are more tightly bound than oxygen, and therefore more stable. If elements lying above this dotted line are condensed (if light) or broken down (if heavy) to form elements below this line, energy is released in the process.

mercury (symbol Hg, atomic weight 200·6) the packing fraction is once more zero. For all elements above this atomic weight the packing fraction is once more positive, rising continuously with increase of atomic weight as far as the heaviest of the natural elements—uranium (see Fig. 12).

Now it is an interesting fact that the elements higher than lead in atomic weight (206) are unstable, and break down in radioactive transformations. This instability is plainly associated with a positive packing fraction and a large number of units in the nucleus. It is now understandable that natural disintegration of an element occurs when the energy of binding of the particles, as represented by the mass defect from a whole number, is not sufficient to ensure stability to the nucleus.

By the end of 1925, therefore, a coherent picture of atomic structure had been built up, to which many different lines of research—radioactivity, X-ray diffraction, mass spectra and optical spectra—had all contributed. And with the knowledge of the nature of the atom went a realization of the prodigious force which bound its parts.

1

THE GROWTH OF NUCLEAR PHYSICS

Artificial Transmutation

The year 1919, apart from inaugurating Aston's classical researches, saw also the publication by Rutherford of a paper which founded a virtually new science—that of nuclear physics. In this paper was given for the first time an authentic account of the artificial transmutation of one element into another, a revolutionary discovery that started people thinking once more about the old alchemists.

Rutherford achieved success by bombarding the nuclei of atoms with fast-moving projectiles of an energy much greater than could be imparted to them by ordinary means. He used as his bombarding agent the alpha particles given off by radium C_1 (see table at p. 36), and observed the scintillations in the direct line of fire on a zinc-sulphide screen. Now when these alpha particles are photographed in a Wilson apparatus they give straight-line tracks which cease abruptly at a distance of almost exactly seven centimetres from their origin. The reason for these straight-line tracks is that the particles are comparatively heavy (mass 4) and fast-moving. They are efficient, therefore, in displacing electrons from atoms in their paths and thus enabling condensation to take place along their line of travel, with consequent cloud formation. Owing to disparity between their mass and that of the electron, however, they are not appreciably deflected by such collisions until, having lost most of their momentum by collision, they are slowed down

sufficiently to capture electrons. They then revert to neutral helium atoms, and no longer cause ionization.

When alpha particles were passed through hydrogen scintillations were observed with the screen at a distance of 29 centimetres from the source. This observation was consistent with helium ions occasionally colliding head-on with hydrogen nuclei and driving the latter forward to the screen. When the hydrogen in the chamber was replaced by oxygen the range was reduced, for an oxygen atom, having a nuclear mass sixteen times that of hydrogen, could not be expected to receive sufficient energy to enable it to travel this distance through an oxygen atmosphere. Actually the maximum range found was 26 cm., and even this was ascribed to the presence of hydrogen impurities—*e.g.*, water vapour—in the oxygen.

Nitrogen, having a mass of 14, could be expected to behave similarly to oxygen; yet Rutherford found scintillations up to a distance of 40 cm. from the source—that is to say, to a distance well beyond that achieved in pure hydrogen. This range could not be ascribed to head-on collision of alpha particles with nitrogen, nor even with hydrogen impurities. After a long investigation to eliminate all possible disturbing causes it was concluded that these unusually long-range particles could only be due to protons produced by actual collision of alpha particles with nitrogen nuclei. Further, since these particles were of longer range than the protons from hydrogen, it was apparent that the interaction of the two colliding particles had liberated energy which was carried away by the resulting fragments, as energy of motion, additional to that obtained from the ordinary energy of collision.

It is usual to place the mass number of the atom at the top left of the chemical symbol, and the nuclear charge at the bottom left. Thus helium, of mass 4 and nuclear

charge 2, is represented by $^{4}_{2}He$. Similarly, nitrogen of mass 14 and charge 7 is represented by $^{14}_{7}N$. This leaves the right-hand lower side for the ordinary numerals indicating chemical combination.

A molecule consisting of two nitrogen atoms both of mass 14 is therefore represented by $^{14}_{7}N_2$, whereas a molecule consisting of one atom of nitrogen of mass 14 and another of mass 15 would be written $^{14}_{7}N\ ^{15}_{7}N$. The reaction which Rutherford had discovered is therefore written:

$$^{4}_{2}He + {}^{14}_{7}N = {}^{17}_{8}O + {}^{1}_{1}H.$$

In words: a helium nucleus of mass 4 has reacted with a nitrogen nucleus of mass 14 to produce a nucleus of mass 17 and another nucleus of mass one. The nucleus of mass 17 so formed has a positive charge of 8, and must therefore be an isotope of oxygen, for only this element has such a nuclear charge. The particle of mass 1 has a single positive charge, and is therefore a proton. It will be seen that both mass and charge numbers balance on each side of the equation. Only a refined estimation of the packing fractions of all four elements involved shows that a minute amount of mass is lost during the transformation, and this mass-loss appears as additional energy of motion of the resulting nuclei, in accordance with the Einstein equation of conversion (p. 45).

The above reference to the isotope of oxygen of mass 17 is the first indication that oxygen is not a simple substance. It was not until 1929, however, that the isotope of mass 17—and also one of 18—was discovered in ordinary oxygen. They were not found by their mass spectra for two reasons: first, because their abundance was small ($^{17}_{8}O$ is present to the extent of four parts in ten thousand, and $^{18}_{8}O$ twenty parts in ten thousand); and, second, because traces of water vapour give rise to lines which mask these two masses.

They were discovered by Giauque and Johnston from an examination of the optical spectrum of water vapour.

Deuterium

The discovery of the oxygen isotopes upset the masses calculated on the scale O = 16·0000, and as a consequence the spectrographic value for H was found to differ perceptibly from the chemical value. It was suspected, therefore, that hydrogen itself was not a single substance. Urey, Brickwedde, and Murphy in 1932 confirmed this suspicion, for they discovered an isotope of hydrogen of mass 2—*i.e.*, ${}^{2}_{1}H$. Owing to the particular importance of this isotope, in which the mass is actually double that of the proton, a separate symbol has been given to it, that of D (deuterium). The deuteron, as the nucleus of the deuterium atom is called, is therefore a particle of mass 2 and charge 1, or ${}^{2}_{1}D$.

Further examination of the light elements under alpha-particle bombardment indicated that many of them suffered disintegration. Aluminium foil, when subjected to the rays, was found by Rutherford and Chadwick to give protons of 90 cm. range. These authors demonstrated their nature by deflection experiments in an electrostatic field.

During the decade 1920–30, however, no further spectacular advances of an experimental nature were made, and the alpha particle obtained from natural disintegration remained the sole means of effecting transmutations. But theoretical developments occurred which were to have an important bearing on the experimental attack.

Wave Mechanics

Bohr's quantum theory of the atom, although achieving remarkable success in interpreting the spectra of hydrogen

and ionized helium, failed for normal helium. Also, the theory was unsatisfactory in so far as it postulated stationary states of the electron in defiance of classical principles of electromagnetism, yet used those principles for determining the electron's path. For these and other more technical reasons modifications were necessary, as Bohr himself was the first to recognize.

The next idea of importance for the subject was put forward by de Broglie in 1924. He suggested that electrons were not mere particles, but had a wavelike nature, and that they were in fact centres of a system of waves. According to Einstein, it will be remembered, waves of radiation deliver up their energy in packets, quants, or photons, of magnitude $h\nu$, where ν (nu) is the frequency of the wave; that is to say, radiation behaves in a way as if it had a particulate nature, and the light quant, or photon, will deliver up all its energy at a particular place remote from its origin, and not—as would, say, a spreading water wave—dissipate its energy over the whole wave front. De Broglie reversed this idea. The electron, he concluded, also had a dual nature—it was both particle and wave. An electron of mass m moving with velocity v has, as we say, momentum mv; and this momentum, according to de Broglie, is directly related to the wavelength of the mechanical waves.

In the theory of optics it is well known that there are phenomena connected with the propagation of light which cannot be explained in terms of the ordinary geometrical conception of rays—*e.g.*, the fact that a ray of light from a narrow slit never casts a sharp shadow of a thin-edged object, but produces instead a fringe of gradually changing intensity. Such behaviour finds a ready explanation in terms of the wave theory of light, which ascribes to radiation a wavelike nature. For distances large compared with the wavelength of the radiation concerned this wave theory is

indistinguishable in its consequences from geometrical optics; but for distances of the same order of magnitude, distinct effects are predicted.

Schrödinger saw that if de Broglie's suggestions were adopted, then the difficulties which confronted the theoretical physicist in describing the behaviour of electrons were analogous to the problems of optics, which had been solved by means of the wave treatment. Starting from the fundamental principle of classical dynamics—the Principle of Least Action (which expresses in one single statement Newton's three laws of motion)—he was able to derive a wave equation for a particle, and to identify the velocity of the particle with the velocity of the wave train represented by his equation.

This wave equation—and it is important for us to notice this—was deduced by a purely classical method of approach, and yet it reproduced correctly the most significant peculiarity of quantum theory—the discrete energy states of a particle. For it was found that the solutions of the equation were none other than those energy values which Bohr had earlier deduced for the hydrogen atom.

The electron is now no longer regarded as a single particle moving along a circular or elliptic path in a single plane, but as something more akin to an electric charge distributed over the whole outer space surrounding the nucleus, and the idea of a localized electron is replaced by the concept of charge density. With this equation as a starting-point Schrödinger succeeded in deducing all Bohr's results, some with greater accuracy, and in addition his method could be applied to more complicated types of electron configuration.

As an experimental confirmation of their wavelike nature G. P. Thomson, in 1927, passed a beam of electrons through a very thin gold foil and was able to photograph diffraction

patterns, thus showing that these charged particles behaved in some ways like X-rays.

The Uncertainty Principle

An alternative way of regarding the problem of quantized energy was propounded by Heisenberg in 1925. He abandoned altogether the idea of a mechanical model of the atom, for he saw that by adhering to what was at best an imperfect analogy physicists were unwittingly fettering their imagination by limitations which had no necessary counterpart in the physical world. He suggested that quantum theory should be founded entirely on relationships between what could be *observed* in atomic processes, as distinct from what could only be *surmised.* Thus spectral frequencies, and hence energy levels, are observable quantities, whereas electron positions in the atom are not, and therefore find no place in Heisenberg's analysis. In connexion with this problem of constructing theory on observables he propounded his famous Principle of Uncertainty. This states that the simultaneous determination with complete exactitude of related physical entities, such as energy and time or position and momentum (mass $\times$ velocity), is intrinsically impossible.

The principle recognizes that any attempt which may be made to examine a system involves some disturbance to that system, and that in the case of minute units, such as electrons or atoms, even light waves may disturb them. There is a well-known effect, discovered by Compton, in which the corpuscular nature of light is clearly brought out. Compton discovered that light waves could collide with electrons. The 'photon' behaves like any other particle in this respect, and suffers a change in energy on collision, so that its frequency (which, as we have seen, is proportional to its

energy) also changes. By means of short-wavelength gamma rays we could, in principle, determine the position of an electron with high accuracy; but owing to the operation of the Compton effect the momentum of the electron would be altered during the determination in an unknown direction, and would be correspondingly uncertain. Alternatively, the Compton disturbance could be reduced to negligible proportions by the use of radiation of long wavelength; but the measurement of position would then become indefinite, for it is impossible to locate a particle to less than the distance represented by a single wavelength. Thus, since all physical observation must be made by physical means which in the process displaces the object observed, it is evident that the limitation on accuracy of measurement is of a fundamental nature. According to Heisenberg the product of the intrinsic errors associated with measuring pairs of variables such as energy and time is of the magnitude of Planck's constant h. Owing to the minute value of this constant it follows that the indeterminacy associated with quantum processes is important only when we deal with magnitudes of the same order of smallness—*i.e.*, atomic processes generally. It is not necessary to use quantum theory when dealing with the macroscopic quantities of everyday life.

The description of atomic phenomena by this scheme starts from certain experimentally determined relationships between the frequencies of spectral lines. In other words, at the very basis of the theory is the concept of discontinuity, and the atom itself is specified in terms of all its discrete frequencies. The mathematical symbol used for this description is known as a 'matrix,' which is an array of quantities specifying, for instance, the various possible energy transitions in the atom. For the most part matrices can be manipulated as ordinary algebraic quantities, but in one respect they differ, for usually the product AB of two

matrices A and B is not equal to the product BA. In technical jargon it is said that the quantities do not commute.

Despite the great differences in physical assumptions and mathematical treatment it is a strange fact that the Uncertainty Principle in the hands of Heisenberg, Born, and Jordon, to mention only a few of the outstanding names associated with the development of the subject, has resulted in a new quantum mechanics which gives all the results of wave mechanics and goes even farther. The most profound investigations along this line of thought have been made by Dirac, who succeeded in combining quantum ideas with the Special Relativity Theory of Einstein. As a consequence he deduced that there must exist a particle of the same mass as the electron, having a charge equal in magnitude but of opposite sign. Such a particle was later discovered by Anderson (1932). It is known as the 'positron,' and is represented by e^+ (or sometimes β^+), whereas the (negative) electron is represented by e^- (or sometimes β^-).

Quantum Mechanical 'Tunnel' Effect

In 1928 Gamow and, independently, Condon and Gurney developed a tentative theory of the nucleus which indicated that a potential barrier existed at its edge, which barred the escape of charged particles confined within. Beyond the barrier the electrical force fell away rapidly according to the inverse-square law of Coulomb, which experiment had shown to hold to within a distance of one million millionth of a centimetre (10^{-12}) from the nucleus. It followed from classical theory that a particle within the crater of this nucleus would have insufficient energy to jump over the top and escape, so that on such principles the escape of an alpha particle from a radioactive nucleus would be impossible. But these authors showed that according to quantum

energy) also changes. By means of short-wavelength gamma rays we could, in principle, determine the position of an electron with high accuracy; but owing to the operation of the Compton effect the momentum of the electron would be altered during the determination in an unknown direction, and would be correspondingly uncertain. Alternatively, the Compton disturbance could be reduced to negligible proportions by the use of radiation of long wavelength; but the measurement of position would then become indefinite, for it is impossible to locate a particle to less than the distance represented by a single wavelength. Thus, since all physical observation must be made by physical means which in the process displaces the object observed, it is evident that the limitation on accuracy of measurement is of a fundamental nature. According to Heisenberg the product of the intrinsic errors associated with measuring pairs of variables such as energy and time is of the magnitude of Planck's constant h. Owing to the minute value of this constant it follows that the indeterminacy associated with quantum processes is important only when we deal with magnitudes of the same order of smallness—*i.e.*, atomic processes generally. It is not necessary to use quantum theory when dealing with the macroscopic quantities of everyday life.

The description of atomic phenomena by this scheme starts from certain experimentally determined relationships between the frequencies of spectral lines. In other words, at the very basis of the theory is the concept of discontinuity, and the atom itself is specified in terms of all its discrete frequencies. The mathematical symbol used for this description is known as a 'matrix,' which is an array of quantities specifying, for instance, the various possible energy transitions in the atom. For the most part matrices can be manipulated as ordinary algebraic quantities, but in one respect they differ, for usually the product AB of two

matrices A and B is not equal to the product BA. In technical jargon it is said that the quantities do not commute.

Despite the great differences in physical assumptions and mathematical treatment it is a strange fact that the Uncertainty Principle in the hands of Heisenberg, Born, and Jordon, to mention only a few of the outstanding names associated with the development of the subject, has resulted in a new quantum mechanics which gives all the results of wave mechanics and goes even farther. The most profound investigations along this line of thought have been made by Dirac, who succeeded in combining quantum ideas with the Special Relativity Theory of Einstein. As a consequence he deduced that there must exist a particle of the same mass as the electron, having a charge equal in magnitude but of opposite sign. Such a particle was later discovered by Anderson (1932). It is known as the 'positron,' and is represented by e^+ (or sometimes β^+), whereas the (negative) electron is represented by e^- (or sometimes β^-).

Quantum Mechanical 'Tunnel' Effect

In 1928 Gamow and, independently, Condon and Gurney developed a tentative theory of the nucleus which indicated that a potential barrier existed at its edge, which barred the escape of charged particles confined within. Beyond the barrier the electrical force fell away rapidly according to the inverse-square law of Coulomb, which experiment had shown to hold to within a distance of one million millionth of a centimetre (10^{-12}) from the nucleus. It followed from classical theory that a particle within the crater of this nucleus would have insufficient energy to jump over the top and escape, so that on such principles the escape of an alpha particle from a radioactive nucleus would be impossible. But these authors showed that according to quantum

ideas the escape process was not impossible, but merely improbable. There was, indeed, a definite possibility, or shall we say probability, of escape by 'tunnelling' through the barrier. Calculation was able to relate the energy of the escaping particle with the probability of its escape, which, in a large sample of the radioactive material, corresponds to its rate of decay. This relation was found to be identical with a quantitative rule which Geiger and Nuttall had discovered many years earlier. They had observed that the more rapid the rate of decay, the longer the range of the alpha rays. This rule holds with such accuracy that it can be utilized for calculating the decay constant of very rapidly decaying substances, from measurement of the alpha-particle range.

The converse of this likelihood of emission is the likelihood of particle capture. Wave mechanics showed that for a nucleus to be able to capture a charged particle it was not necessary for the particle to possess sufficient speed to enable it to get right over the barrier; it was only necessary to accelerate it with comparatively moderate voltages for the tunnel effect to become operative and permit of the entry of particles into the nucleus. It followed from these considerations, however, that the probability of penetration increased rapidly as the velocity of the projectile increased. Gamow pointed out that capture should occur at quite moderate speeds with protons as bombarding agents, and this possibility provided the necessary inducement for the experiments carried out by J. D. Cockcroft and E. T. Walton with protons accelerated by potentials of a few hundred thousand volts.

Controlled Disintegration

Until 1932 all artificial transmutations, as we have seen, had been effected with the high-energy alpha particles given

out by the natural decay of radioactive substances. Although the possibilities of making new discoveries with this projectile had not by any means been exhausted (two important additions to knowledge were shortly to be made by its means), the use of the proton as a bombarding agent could

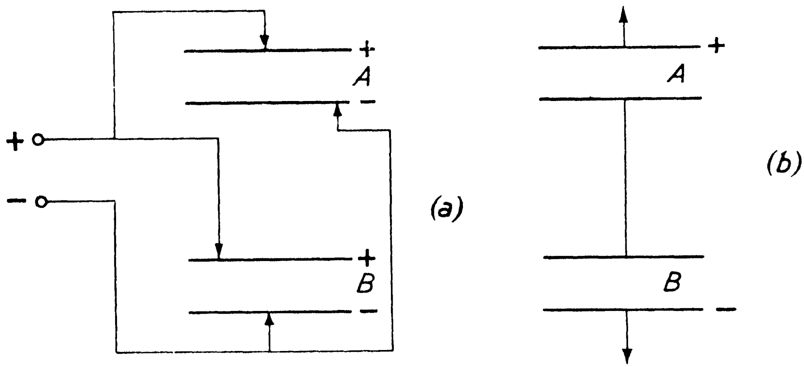


FIG. 13. THE PRINCIPLE OF THE COCKCROFT AND WALTON METHOD

be expected to produce changes not obtainable with alpha particles; and also, since the proton carried only one positive charge as compared with two on the alpha particle, it should more readily overcome the repulsion of the nucleus of the heavier atom—*i.e.*, of those carrying a large number of positive charges.

Cockcroft and Walton's method consisted in principle of charging electrical condensers in parallel and discharging them in series across a specially constructed vacuum tube insulated to withstand very high voltages. Fig. 13 (*a*) shows two condensers, *A* and *B*. If the supply is at, say, 1000 volts, then each of the condensers *A* and *B* will be charged to this voltage. When the leads are removed and the lower plate of *A* is connected to the upper plate of *B*, as in Fig. 13 (*b*), then these two joined plates will be at the same potential. The *upper* plate of *A* will now be at a voltage of 2000 above

the *lower* plate of *B*, and thus two condensers charged in parallel at 1000 volts will yield a voltage twice this when connected in series.

By such means a potential of 800,000 volts was obtained, and protons produced by the ionization of hydrogen atoms were accelerated by this voltage and used to bombard a target consisting of a thin layer of the element lithium. Lithium is one of the light elements, having a nuclear charge of only 3 and naturally occurring isotopic masses of 6 and 7, of which the latter is much the more abundant. Owing to its low charge—and hence low nuclear barrier—the element is obviously a very suitable choice for attempted disintegration.

The results obtained by Cockcroft and Walton may be summarized in the equation:

$$^{7}_{3}\mathrm{Li} + {}^{1}_{1}\mathrm{H} \longrightarrow 2\,^{4}_{2}\mathrm{He}.$$

Thus for every proton captured two helium nuclei were produced. These were actually identified by means of their cloud-chamber tracks, from the lengths of which the energy associated with their motion could be measured. Now the mass of the lithium isotope 7 plus that of the proton amounts to 8·0261, according to Aston, whereas the mass of two helium nuclei amounts to only 8·0078, so that the mass defect in the reaction is 0·0183. This mass, expressed as energy by the Einstein equation, added to the energy of motion of the bombarding proton was found within experimental error to be equal to the energy of motion of the liberated helium nuclei, thus affording experimental verification of mass-energy conservation.

The Electrostatic Generator

Another device for producing high voltages, based on a quite different principle, was published shortly afterwards

by Van de Graaff. This apparatus is the electrostatic generator (Fig. 14). An electric charge from a high-voltage rectifier

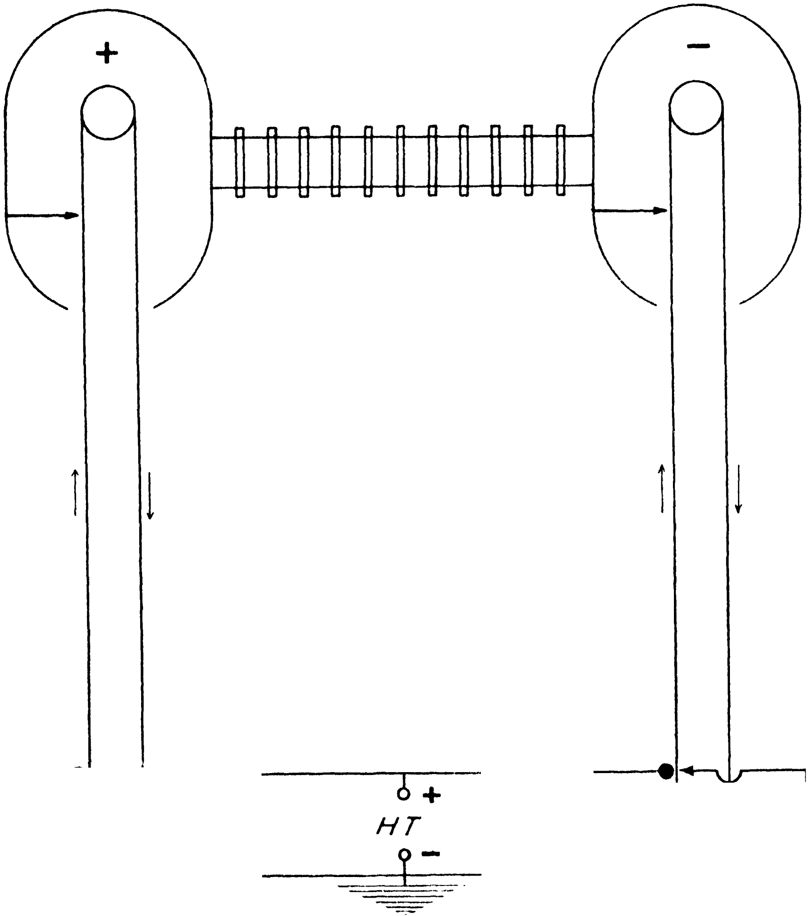


FIG. 14. AN ELECTROSTATIC GENERATOR

is imparted to an insulated endless belt, which is made to revolve and carry the charge into the interior of a large hollow metal sphere, about fifteen feet in diameter. The charge is collected off the belt by a system of needles almost

touching the latter and transferred to the sphere, which it raises to a high potential (voltage). Two such spheres are charged, one positively and the other negatively, and a very high potential difference is set up. Between these two spheres is a large exhausted tube, through which the discharge takes place. The limit to the voltage which may be built up is set by the breakdown of the air in the vicinity of the electrodes, which eventually ionizes under the electrostatic strain, and therefore become electrically conducting. A discharge then occurs, with production of a corona. If the generator is enclosed within a tank of compressed air much higher voltages may be obtained before breakdown occurs. Potentials up to five million volts have been realized, although the breakdown of insulation of the discharge-tube limits the value which may be used for accelerating ions to about 2·2 million volts.

It is interesting to compare the energy of protons accelerated through such a field with the energy of the naturally occurring alpha particles. A simple calculation shows that for protons to have the energy of radium C_1 alpha particles they would need to be accelerated through a potential of nearly eight million volts. Thus the above machine will produce projectiles of about one-quarter the energy of those obtained from natural radioactive sources. The great advantage of the artificially produced bombarding particles is the quantity in which they can be produced. Thus one milligram of Ra-C_1 gives off about 36 million particles per second, of which one in a million succeeds in effecting disintegration.. This quantity of electricity shot off per second amounts to about 10^{-11} ampere, whereas currents 100,000 times this, or even more—*i.e.*, currents of 10^{-6} ampere and upward—may be obtained by artificial means. Nevertheless, the Gamow-Condon-Gurney theory indicates that the yield of disintegration will increase very

rapidly with the rise in bombarding voltage, so that for effective transmutation higher voltages still are necessary.

The Cyclotron

But the most startling and significant advance in high-voltage physics was yet to come. It was the invention of

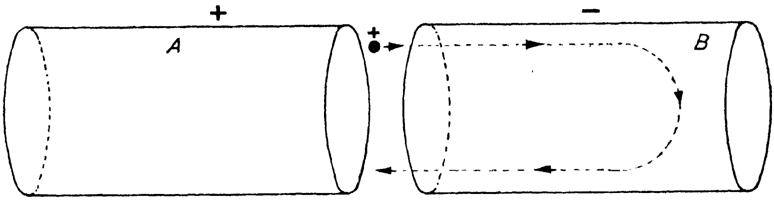


FIG. 15. THE PRINCIPLE OF THE CYCLOTRON

A charged particle will be acted on by electric forces only when it is in the gap. But magnetic forces will act independently of the intervening conducting shield.

the 'cyclotron,' announced by Lawrence and Livingston in 1933. This instrument has the great advantage over the previous arrangements described in that no accelerating tube is required, and the difficulties associated with its insulation do not therefore arise.

The method which was used by these workers to accelerate ions is extremely ingenious.

It is a well-known property of electric charges that they collect entirely on the outer surface of a conductor. Thus imagine two hollow metal cylinders separated from one another by a short distance; if one cylinder, *A*, is charged to a higher voltage than the second there will exist an accelerating field in the gap, and a positively charged ion in this gap will experience a force accelerating it to the cylinder of lower potential, *B* (Fig. 15). When the ion enters the interior of *B*, however, it will experience no electric force due to this field, but will continue forward with the velocity that it acquired in falling through the potential across the

gap. While the ion is within *B* it is possible to vary the charge on *B* without affecting the ion in any way. If, for example, *A* and *B* are connected to an alternating-current supply, then the potential on *B* will rise, so that it eventually becomes greater than *A* by just as much as *A* was greater than *B* initially. Supposing now that by some means the ion is turned round, without losing its speed, and reaches the gap at *B* when *B* is positive with respect to *A*, the ion will now accelerate across the gap in the direction of *A* and increase its velocity still further.

This is precisely what is accomplished in the cyclotron. Two D-shaped hollow metal segments lie in a horizontal plane with a small gap separating them, and well insulated from each other. The 'dees,' as they are called, lie between, and are completely covered over their flat surfaces by, the poles of a powerful electromagnet. The dees are further connected to a source of high-voltage, high-frequency current obtained from a system of valve oscillators (virtually a high-powered wireless transmitter).

It has already been remarked that an electric charge in motion is deflection by a uniform magnetic field acting perpendicularly to its motion, and thereby constrained to move in a circle. Referring to Fig. 16, we see that if an ion is generated at a point *B* within the gap at a time when the dee *D* is at a higher potential than dee D_1, then it will be accelerated across the gap to D_1, and disappear within the hollow, and cease to be acted on by electrical forces. It will therefore cease to accelerate, and continue with constant speed. Under the influence of the magnetic field, acting at right angles to the plane of the paper, it will, however, travel with uniform peripheral speed along the circumference of a circle, and therefore emerge travelling in the opposite direction into the gap. If it is arranged, as can easily be done, by a suitable choice of magnetic field and frequency, that the

ion emerges into the gap when D_1 is reversed in voltage with respect to D, then the ion will accelerate across the gap to D, and describe a further semicircle within the

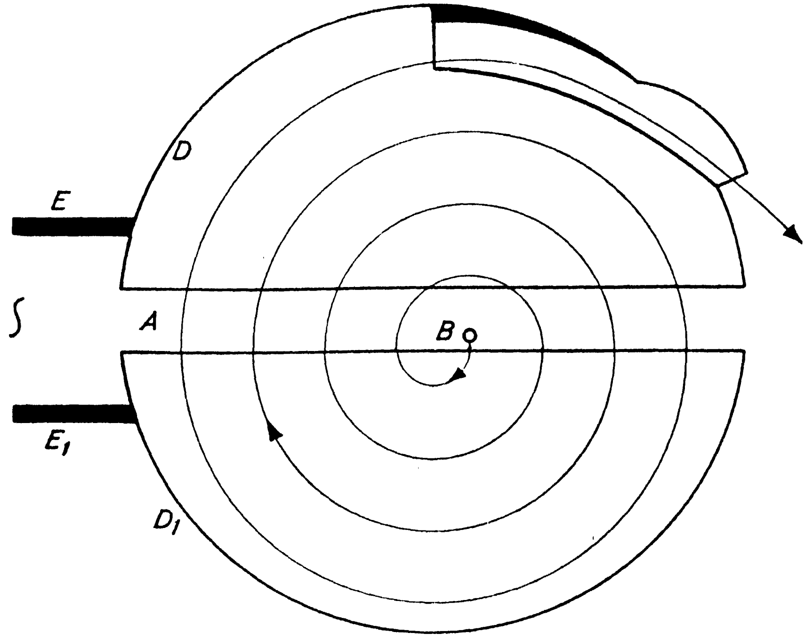


FIG. 16. DIAGRAM OF THE CYCLOTRON

The dees (D, D_1) are energized by high-frequency, high-voltage supply, through the electrodes E, E_1. Acceleration of ions takes place across the gap A. B is a heated filament which gives off electrons and 'ionizes' gas molecules in its vicinity. When ionized the atoms are swept away by the electric force acting across the gap, and describe the spiral shown. The poles of the magnet (not shown) have their surfaces in the plane of the paper and cover completely both gap and dees.

latter. The radius of this semicircle will be slightly larger than the first, however, because of the greater speed of the particle. It happens that the increased distance that the particle has to travel in this larger circle is exactly balanced by its increased speed, so that the time of travel before it emerges once more is identical for every segment travelled. This means that, providing the alternating frequency

remains constant, the particle will always emerge at the gap at the instant required for effective acceleration across it. The path of such a charged particle will therefore be a spiral, and a beam of particles may thus be produced, and led out by means of a suitable electrostatic deflector placed near the outer edge of the cyclotron.

If the alternating current is supplied at 50,000 volts, and the ion completes a hundred cycles, it will cross the gap 200 times. At each traverse it will receive an acceleration of 50,000 volts—that is, 200 × 50,000, or 10,000,000 volts in all. For a singly charged ion the energy gained will be the product of this voltage and the charge—namely, unit electronic charge (the magnitude of the charge lost by the ion when its atom loses one electron). The energy is expressed as 10,000,000 electron-volts, or 10 M.e.v. for short. For doubly ionized particles—*e.g.*, helium atoms less two electrons—the energy would be double this, or 20 M.e.v. It is thus apparent that the cyclotron is able to produce particles of energy greater than those from many of the natural radioactive elements.

In 1939 a cyclotron was under construction to provide particles with energies up to 300 M.e.v., but it was not completed. Instead it was diverted to use for war purposes, as described later. It is likely to come into use in the near future, however, when extremely important advances may be expected.

At such high energies the relativity increase in mass upsets the resonance effect—that is, the particles on their outermost journey take longer to traverse the semicircular path than they do for the innermost journey. To correct this it has been proposed to modify the design of the magnets so that the magnetic field increases towards the edges. This will make the tracks more curved, and hence lessen the time of travel.

The cyclotron has been used for accelerating protons, deuterons, and helium ions, both singly and doubly charged. Helium ions, of course, are identical with alpha particles, and it is interesting to note that transmutation results obtained with artificial alpha particles are identical with those obtained with the naturally occurring ions of the same energy.

The considerations which govern the acceleration of ions in this instrument are much the same as those mentioned in the description of the mass spectrograph. Only ions having the same value of e/m can be accelerated under given conditions of frequency, voltage, etc., and by a suitable choice of gas pressure (always very low, of course—about 10^{-5} mm. of mercury) even particles having almost identical values of e/m, such as deuterons and singly charged hydrogen molecules, may be separated. The hydrogen molecule, being larger, collides more readily with the residual air in the dees and loses its speed, so failing to keep in resonance with the changing electrical pulse. The deuteron alone may thus be accelerated, and a pure beam of almost uniform energy obtained. If the beam is led out through a thin window into the atmosphere it produces intense ionization, melting small metal objects in its path. The beam from a 16 M.e.v. cyclotron penetrates about five feet of air. Currents of several hundred microamperes (μa, or 10^{-6} amp) may be obtained.

The cyclotron is now used extensively for the production of high-voltage ions, since at present much higher energies may be imparted to charged particles by this than by any other instrument. It is inferior to the previous two methods, however, in one respect—that the stream of ions produced is less uniform in energy. A consideration of the results obtained with it will be deferred to the end of the chapter. In the meantime we shall revert for a moment to the consideration of discoveries already hinted at, which were made

during researches on Ra-C alpha-particle bombardment of various elements.

The Neutron

In 1930 Bothe and Becker discovered that the bombardment of the element beryllium (also called glucinum) with alpha particles caused the emission of a very penetrating gamma (γ) radiation. This radiation, as has been seen, is electromagnetic in nature and similar to X-rays, but of much higher frequency and, therefore, energy. The radiation was found to be capable of setting free protons from substances containing hydrogen, helium, or carbon, and these protons moved with very high velocity. From an analysis of the masses and penetrations of the particles concerned in the reaction Sir James Chadwick concluded that radiation alone could not be responsible for this. To impart such velocities to the protons would require an energy of 55×10^6 electron volts, while the amount of energy which the bombardment of beryllium could release, as calculated from mass-energy relationships, was very much less. Also, such gamma rays would be expected to release electrons in passage through matter, whereas Wilson Chamber experiments showed no tracks. It was found that the bombarding

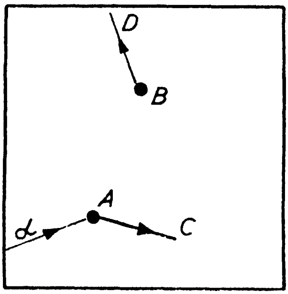


FIG. 17. BEHAVIOUR OF NEUTRONS IN THE CLOUD CHAMBER

An alpha particle from a disintegrating radon nucleus strikes a beryllium nucleus, *A*, which then disintegrates into two particles. One is shown moving in the direction *AC*, ionizing atoms as it travels. The other particle, a neutron, exhibits no visible track, but its travel from *A* to *B* is inferred from the ionization track *BD* resulting from collision of a neutron with an atomic nucleus. (*Note*: Cloud-chamber *photographs* show a white trail on a black background.)

alpha rays produced tracks, and so did the struck particle, and that some distance away from the collision a proton track started, apparently from nowhere (Fig. 17). In 1932 Chadwick was able to explain these difficulties by postulating the existence of the neutron—a particle whose mass he calculated to be approximately equal to that of the proton, but which carried no electrical charge whatever. Further work has substantiated this explanation of the phenomena, and neutrons have since been discovered in numerous other reactions. A mixture of beryllium powder and radium emanation (to supply the alpha particles) still remains one of the most convenient methods of producing neutrons. This reaction may be expressed:

$$^{9}_{4}\mathrm{Be} + ^{4}_{2}\mathrm{He} \longrightarrow ^{12}_{6}\mathrm{C} + ^{1}_{0}n.$$

The symbol $^{1}_{0}n$ for the neutron indicates that it has unit mass and no charge.

This absence of charge makes the neutron an extremely effective agent for accomplishing transmutation, for it is not repelled by the nuclear charge of the atom with which it collides, nor is it slowed down by the outer electrons. Since the potential barrier of the nucleus is inoperative against neutrons, the latter are particularly useful in effecting changes in the nuclei of the heaviest atoms, whose nuclear charge is so high as to prevent proton entry. For the same reason a fast neutron can penetrate many inches, or even feet, of a heavy element such as lead, since the size of the nucleus, as we saw earlier, is minute compared to the size of the atom, and only a direct nuclear collision can impede a neutron. In a glancing collision with a heavy nucleus the energy loss will be small (unless, of course, capture takes place), just as a ball will bounce off a wall with little loss of speed. If, however, the neutron is made to pass through a medium containing nuclei of low atomic weight, such as

water or paraffin wax, in which the number of hydrogen atoms per unit volume is large, the speed of the neutron will be reduced rapidly to that of the ordinary thermal motion of the atoms. When two approximately equal masses—proton and neutron—collide there will be considerable transference of energy from the faster to the slower. Such slow, or thermal, neutrons often behave differently from fast neutrons in subsequent reactions.

Artificial Radioactivity

The year 1934 saw a discovery of considerable significance. In that year I. Curie and F. Joliot discovered the phenomenon of artificial radioactivity. Until then it had been thought that radioactivity was exclusively a property of the heavier elements, but the above investigators discovered that the bombardment of thin aluminium foil with alpha particles from Ra-C produced positrons, and that after the source had been removed emission of positrons continued, decaying according to the usual manner of naturally occurring radioactive substances. It will be remembered that Rutherford and Chadwick some years earlier had discovered protons to be emitted in this reaction. As finally elucidated, this is what happens:

$$\begin{array}{l} {}^{27}_{13}\mathrm{Al} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{30}_{15}\mathrm{P} + {}^{1}_{0}n \\ \qquad\qquad\qquad\qquad\quad \downarrow \\ \qquad\qquad\qquad\qquad {}^{30}_{14}\mathrm{Si} + e^{+}. \end{array}$$

First, an isotope of phosphorus is formed, together with a neutron. This phosphorus isotope is unstable and radioactive. It breaks down, half of it disappearing every 155 seconds, to form a stable silicon atom and a positron. Thus either a neutron plus a delayed positron is emitted, or a proton. The latter reaction occurs twenty times as often as

the former. Many other reactions producing positrons are now known, as, for example, the bombardment of carbon with protons, and also the interaction of hard gamma rays with metals. Thorium C^1 gamma rays, with energies of $2\frac{1}{2}$ M.e.v., produce positron-electron pairs when absorbed by a lead target.

Heavy Water

Reference has already been made to the fact that the isotope of hydrogen, mass 2, called deuterium ^2_1D, had been discovered in 1932. Washburn and Urey found that prolonged electrolysis of water resulted in a concentration of the heavier isotope to a measurable extent in the residual liquid.

Since the mass of a deuterium atom is roughly twice that of a hydrogen atom, the weight of a molecule of deuterium oxide will be $2 \times 2 + 16 = 20$, whereas a molecule of water, H_2O, will be $2 \times 1 + 16 = 18$. Thus deuterium oxide is $\frac{20}{18}$, or $1\frac{1}{9}$, times as dense as ordinary water. It is often referred to, for this reason, as 'heavy water.'

The vapour of deuterium oxide when subjected to electron bombardment yields deuterons. Such deuterons produced within the cyclotron may be accelerated to many millions of volts, and then used as transmuting agents.

Results of Bombardment

During the next few years to 1939 a tremendous number of reactions were investigated by means of these various projectiles, of which only a few of the more important will briefly be sketched here.

Disintegration by means of fast-moving protons has been found to take place in no fewer than four different ways, according as a deuteron, neutron, alpha particle, or gamma

ray is ejected from the impacted nucleus. These reactions are referred to as (*p:d*), (*p:n*), (*p:α*), and (*p:γ*) respectively, the first in the bracket referring to the transmuting agent and the second to the particle ejected. It has been found that, generally, protons are only effective in causing disintegration in the lighter elements, up to atomic number 19; above this, apart from a few (*p:n*) reactions, the nuclear barrier has so far proved insurmountable. The reaction

$$^{9}_{4}\mathrm{Be} + ^{1}_{1}\mathrm{H} \longrightarrow ^{8}_{4}\mathrm{Be} + ^{2}_{1}\mathrm{D}$$

is unusual in that deuterons are emitted as a consequence of proton bombardment of beryllium. The element boron, of atomic number 5, breaks up completely, to give three helium nuclei on proton bombardment.

Bombardment by means of deuterons shows an even greater variety of phenomena, in some instances several dissimilar particles being ejected. Thus gold emits a proton and an alpha particle, and nitrogen breaks down to four alpha particles. The bombardment of deuterium by means of deuterons may follow one of two ways:

$$^{2}_{1}\mathrm{D} + ^{2}_{1}\mathrm{D} \longrightarrow ^{3}_{1}\mathrm{H} + ^{1}_{1}\mathrm{H},$$

in which a new isotope of hydrogen, of mass 3, is formed, or:

$$^{2}_{1}\mathrm{D} + ^{2}_{1}\mathrm{D} \longrightarrow ^{3}_{2}\mathrm{He} + ^{1}_{0}n,$$

in which an isotope of helium, mass 3, which is unknown in nature, results. There is some evidence that the isotope of hydrogen, mass 3, tritium, exists naturally in minute concentration, but no measurable separation has ever been effected.

Experience has shown that deuterons of a given energy are more effective than protons in causing transmutation. The deuteron, unlike the neutron, can, of course, be accelerated in an electric field in virtue of the charge it carries. According to Oppenheimer and Phillips the deuteron, consisting of a proton and neutron in close combination, is

affected by the presence of the nuclear charge of the bombarded atom, so that the bond is weakened. The proton, therefore, is repulsed and flies off, leaving the fast neutron to be captured. Disintegration of the isotopic nucleus so formed may or may not follow. Often gamma radiation is emitted at the same time as particles.

Deuterons react with heavy elements chiefly by neutron capture, as in:

$$^{209}_{83}\mathrm{Bi} + ^{2}_{1}\mathrm{D} \longrightarrow ^{210}_{83}\mathrm{Bi} + ^{1}_{1}\mathrm{H}.$$

With lighter elements, however, protons may be captured and neutrons escape. Fast deuterons produce in lithium and beryllium targets intense neutron beams, several hundred times stronger than those given by the radon-beryllium method.

Several instances of alpha-particle disintegration have already been referred to. Owing to the double charge carried by these particles they are not effective in promoting nuclear reactions of the heavier elements; but helium nuclei accelerated to very high voltages in the cyclotron have been used against elements such as titanium (atomic number 22) and nickel (atomic number 28) with resultant ejection of protons.

A typical reaction yielding a beta radioactive element is:

$$\begin{array}{l} ^{25}_{12}\mathrm{Mg} + ^{4}_{2}\mathrm{He} \longrightarrow ^{28}_{13}\mathrm{Al} + ^{1}_{1}\mathrm{H} \\ \qquad\qquad\qquad\qquad\quad \downarrow \\ \qquad\qquad\qquad\qquad\ ^{28}_{14}\mathrm{Si} + e^{-}. \end{array}$$

So far, little indication has been given of the effect of accelerating voltage on the process of transmutation, but experiment has shown that there are definite energy levels in the nuclei just as in the outer electronic layers. Thus capture of a particle, whether alpha particle, neutron, or proton, may take place strongly over a narrow and quite critical energy

of bombardment, whereas below and above this energy band the absorption is small. Many such levels usually exist in the nucleus, but their explanation awaits a comprehensive nuclear theory. High-energy gamma rays are also known to effect disintegration of both light and heavy elements, although only a few reactions have been studied. The rays from thorium C^{11} (2·6 M.e.v.) react with deuterons to give neutrons:

$$^{2}_{1}\mathrm{D} + \gamma \longrightarrow {}^{1}_{1}\mathrm{H} + {}^{1}_{0}n.$$

From this reaction the mass of the neutron has been determined with some accuracy as 1·00897, compared with 1·00813 for hydrogen (proton) and 0·00055 for the electron or positron ($^{16}\mathrm{O} = 16{\cdot}0000$).

Physiological Effects

An artificially radioactive substance which is likely to prove of considerable therapeutic importance in the future was obtained by Lawrence from bombardment of the metal sodium (present, you will recollect, combined with chlorine, as sodium chloride or common salt) with 2 M.e.v. deuterons:

$$^{23}_{11}\mathrm{Na} + {}^{2}_{1}\mathrm{D} \longrightarrow {}^{24}_{11}\mathrm{Na} + {}^{1}_{1}\mathrm{H}.$$

This isotope of sodium is radioactive, and gives out electrons and gamma rays, finally ending as magnesium.

$$^{24}_{11}\mathrm{Na} \longrightarrow {}^{24}_{12}\mathrm{Mg} + e^{-} + \gamma.$$

Radio-sodium decays rapidly (half-life 15 hours), and weight for weight it is about ten million times more active than radium. It can be produced in perceptible quantities from cyclotron currents of a few microamperes, so that quantities equivalent in intensity to kilograms of radium can be made available comparatively cheaply. Both sodium and the end-product magnesium are harmless to human life, especially

in the minute quantities necessary for treatment, and since the substance has decayed to negligible activity within a week it may be left in the body without causing injury. It seems possible that radio-sodium will eventually supersede radium in the treatment of malignant growths.

Within the last few years the action of neutrons on tissues has been studied, and neutron-therapy shows promise of being more efficient than X-rays. Whereas neutrons are roughly four times more effective than X-rays in destroying malignant tissue they are only three times as lethal against normal tissue. Consequently it is possible to obtain a greater differentiation in action, although it cannot be said that the treatment is at all specific.

The physiological effects of these various kinds of rays, neutrons and gamma rays especially (alpha and beta rays are less penetrating, and therefore somewhat less dangerous), necessitate that precautions be taken to absorb them. The cyclotron, for example, is usually surrounded by tanks filled with an aqueous solution of cadmium chloride, which absorbs neutrons most effectively. X-rays and gamma rays, on the other hand, require several inches of lead for effective stopping, the minimum thickness depending on the penetrability, or 'hardness' (*i.e.*, frequency), of the radiation. We return now to a consideration of the physical behaviour of these particles.

Slow Neutrons

Neutrons which are produced in disintegrations are invariably of high energy, and generally penetrate all but the lighter elements with but little absorption. When these particles are slowed down, however, they will be in constant thermal collision with the nuclei of any substance irradiated; and since there are no forces of repulsion operating it is possible for them to enter any nuclei with which they may

collide. Thus Fermi's technique of passing neutrons from a generating source through a hydrogen-rich layer an inch or so in thickness, and then using these slow neutrons as bombarding agents, has enabled transformations to be effected in most elements. Since no charge is taken into the nucleus on capture of a neutron there results merely an increase of one unit of mass, and an isotope of the original element is produced. This compound nucleus is unstable, however, and usually emits immediately an alpha particle, proton, or gamma ray, then decays with emission of beta rays (or positrons).

A rather interesting type of reaction occurs when the element potassium, an alkali metal, is bombarded with slow neutrons. There results an immediate emission of two neutrons:

$$^{39}_{19}K + ^{1}_{0}n \longrightarrow ^{38}_{19}K + 2^{1}_{0}n,$$

and the potassium isotope so formed decays with emission of a positron to form an isotope of the inert gaseous element argon:

$$^{38}_{19}K \longrightarrow ^{38}_{18}A + e^{+}.$$

It might be thought that since the neutrons are regenerated—and, indeed, increased—in the reaction, the process once started would continue until all the potassium had been used up. If this were to happen there would result an immense production of energy, for the latter reaction is accompanied by a release of over 2 million electron-volts of energy per nucleus disintegrated; but for several reasons it does not. One is the existence of an alternative process competing with the two-neutron emission—namely, proton emission—and this reaction predominates.

The chief interest in nuclear reactions at present, however, is concerned with the effect of neutrons on the very heaviest elements, uranium and thorium—precisely those which up

to the present have been most resistant to disintegration by means of charged particles. The consideration of such experiments brings us immediately to the very core of the problem of exploiting the immense energies released in nuclear transmutations, but this work requires a chapter to itself.

Source of the Sun's Energy

An interesting outcome of the discovery of these phenomena has been the formulation by Bethe and Weizacker of a series of nuclear changes, all of which have been investigated in the laboratory, which reveal the origin of the sun's energy.

From various physical arguments it is believed that the internal temperature of the sun and other similar stars is roughly 20,000,000° C. At this temperature a minute proportion of atomic particles have thermal motions corresponding to a million volts or so. Also, spectroscopic examination of the sun's disc indicates the presence of the elements hydrogen, carbon, and nitrogen, of which the first is almost completely ionized—*i.e.*, present as protons. The above authors suggest that the following reactions take place under these conditions:

$$\underset{\text{carbon}}{{}^{12}_{6}C} + \underset{\text{hydrogen}}{{}^{1}_{1}H} = \underset{\text{nitrogen}}{{}^{13}_{7}N} + \underset{\text{photon or gamma ray}}{\gamma}$$

$${}^{13}_{7}N = {}^{13}_{6}C + \underset{\text{positron.}}{e^{+}.}$$

This carbon isotope now reacts with a further proton:

$${}^{13}_{6}C + {}^{1}_{1}H = {}^{14}_{7}N + \gamma \text{ (second photon)}$$

and:

$${}^{14}_{7}N + {}^{1}_{1}H = {}^{15}_{8}O + \gamma \text{ (third photon).}$$

The ${}^{15}_{8}O$ oxygen isotope is unstable and positron-emitting:

$${}^{15}_{8}O = {}^{15}_{7}N + e^{+} \text{ (second positron).}$$

Finally:

$$^{15}_{7}N + ^{1}_{1}H = ^{12}_{6}C + ^{4}_{2}He.$$

Beginning with the common isotope of carbon, $^{12}_{6}C$, four protons are eventually absorbed and two positrons emitted. Then this mass accretion is split off as a helium nucleus, and the original carbon nucleus is regenerated. No change, therefore, takes place in the concentration of the carbon; the net result is the condensation of four protons to form a helium nucleus, with the consequent mass defect appearing ultimately as thermal energy—due to the agitation induced by the two positrons and three photons emitted. Calculation from the known density of the sun—deduced from its gravitational effect and size—shows that it is composed largely of hydrogen. From the concentration of protons and carbon, and the rate of the reaction as measured in the laboratory, it has been possible to deduce a value for the total output of energy which corresponds with that measured by observations of its radiation; also the equilibrium temperature deduced accords with the above-mentioned value obtained by other means.

It has not been found possible to construct a cycle utilizing elements of atomic number less than that of carbon, and Bethe and Weizacker have shown that with higher atomic numbers the increased nuclear charge would reduce the probability of proton capture, and hence the energy output, to a point where it would be no longer sufficient to sustain the known losses. The above cycle of transmutations represents, therefore, the most likely source of the seemingly inexhaustible energy of the sun.

IV

NUCLEAR FISSION

Neutron Absorption in Uranium and Thorium

Shortly after the discovery of the neutron Fermi and his collaborators investigated the effect of this particle on the heaviest elements known—thorium, of mass 232 (atomic number 90), and uranium, of mass 238 (atomic weight 238·2, atomic number 92). They found that irradiation of the latter element caused a beta radioactivity to develop. Now emission of beta rays or negative electrons must presumably leave the uranium nucleus with one positive charge more than it possessed previously, and hence a substance of atomic number 93 should be formed:

$$^{238}_{92}\mathrm{U} + {}^{1}_{0}n \longrightarrow {}^{239}_{92}\mathrm{U} \longrightarrow {}^{239}_{93}\mathrm{X} + \beta^{-}.$$

This substance would be an element of atomic number greater than any discovered in nature, a so-called trans-uranic element.

But the phenomenon was not so simple as this, for on detailed examination the induced radioactivity was found to be of great complexity. Instead of the simple die-away curve of radioactive decay shown in Fig. 6 (p. 33) a very complicated curve, indicating a large number of different decay periods, was obtained. Various substances (present, of course, in unweighable quantities) were separated by chemical means and shown to have properties which could be attributed to elements of greater atomic number than uranium, according to their assumed position in the Periodic

Table. This prediction of chemical properties was based on considerations similar to those discussed by Mendeleev in his successful anticipation of then unknown elements (p. 20).

The large number of radioactive elements produced, and the fact that some of them could not be fitted into the table, cast doubt on this explanation, and an attempt was made to treat them as isotopes of thorium, radium, etc. This too was unsatisfactory. Next I. Curie and P. Savitch in 1938 made the significant observation that one of the radioactive products had a decay curve similar to that of a known artificially prepared radio-element, the rare-earth lanthanum (atomic number 57). With this as a guide Hahn and Strassman carried out further experiments, looking particularly for elements in this region of the table. As a result they found a radioactive barium (atomic number 56). Continued investigation has revealed the presence of many radioactive elements with atomic numbers between 35 and 57, whose decay periods and chemical properties are identical with the common elements of these numbers, made radioactive artificially. (It should be remembered that artificial radio-elements, by whatever method prepared, have *chemical* properties identical with non-radio-elements of the same atomic number.)

Fission of the Uranium Nucleus

Previous conclusions about the formation of transuranic elements could not, therefore, be accepted, and it was realized that a new type of disintegration had taken place. Until 1939 the only kinds of particles which had been identified as emissions from radioactive substances were alpha rays (helium nuclei), beta rays (negative electrons), and gamma rays (photons) from naturally unstable elements, and, in addition, protons, neutrons, positrons, and deuterons

from artificial radio-substances. Evidence was now at hand, however, to show that the heaviest element could break up into at least two fragments of approximately equal size. In actual fact it has been found that with slow neutrons the mass ratios of the two fragments are approximately 5 : 7, but approach 1 : 1 as the energy of the bombarding neutrons is increased. To this new type of disintegration the name of 'nuclear fission' has been given.

The extremely complex nature of the fission process is indicated by the fact that at least fifteen decay fragments produced directly from the parent nucleus have been identified, and these in their turn disintegrate with emission of either beta or gamma radiation or both. The decay periods vary from a few seconds to several months. Cloud-chamber photographs have shown that the fission-fragments produce intense ionization along their paths. These are branched like the leaves of a fern, indicating that many particles are struck by the recoiling particles and in their turn have sufficient energy to provoke further ionization. From measurements of recoil it has been calculated that about 170 M.e.v. of energy are liberated by a single dividing nucleus, and this value is in agreement with the mass loss calculated from the packing fractions of the initial and resultant nuclei.

But radio-elements are not the only products of the reaction. Owing to the tremendous amount of energy released it was to be expected that neutrons also might be expelled during fission, for disintegration experiments had indicated that the binding energy of a neutron in a heavy element is of the order of a few million volts only. Von Halban, Joliot, and Kowarski tested this possibility, and found that each nucleus produced on an average about 3 neutrons either during or soon after fission. An experiment by Feather has since shown that the neutrons are certainly released within one million millionth (10^{-12}) of a second afterwards, so it

may be assumed that they are produced during the actual reaction.

Chain Reaction

The great practical importance of this discovery is, of course, that it suggested a reaction which, once initiated, would proceed of its own volition, for every neutron released might itself initiate a further fission, with production of three further neutrons. So an ever-widening chain reaction, with production of immense surplus energy at each step, would take place.

Until this latest discovery was made radioactivity phenomena had taken place on an unweighable scale, and this branch of science had been built up often, as in cloud-chamber experiments, on the results of observations with single atoms. However great the energies released in such individual transformations, they were still detectable only by the most refined methods, and had no significance whatever from the engineering standpoint. The most powerful naturally occurring radio-element, radium itself, gives out 34 thousand million particles per second per gram of radium. This seems a stupendous number until it is remembered that there are nearly two thousand seven hundred million million million atoms in that sample, so that the weight of element disrupted in one second is only (roughly) $\frac{1}{13,000,000,000,000}$ gram. The heat energy liberated has already been mentioned (Chapter I), and since no known means exists for hastening its liberation there is, at least at present, no expectation of natural radioactivity being used as a source of power.

But if the chain reaction could be allowed to branch until many thousand times this number of atoms were disintegrating per second, then power would be available on an engineering scale. Indeed, in the absence of control the rate

of liberation might increase explosively. This does not happen in everyday life, however, and it is apparent that uranium is not at the mercy of any stray neutron which might initiate a decomposition of incalculable violence. If it were it would long since have disappeared, and with it the earth as well. Plainly there are other factors concerned.

Transuranic Elements

Further advance followed from a study of the products of uranium irradiated with neutrons of varying energies of bombardment. A rather anomalous result was obtained, for whereas thermal neutrons of energies a fraction of one electron volt caused fission, with its attendant phenomena, neutrons of about twenty-five volts were absorbed strongly by the element, with production mainly of beta-ray activity. Above this voltage, however, fission reappeared, and grew in intensity as the bombarding energies were increased to millions of volts. The explanation of the absorption of neutrons of about twenty-five volts was realized to be due to what is known as wave-mechanical resonance. It has already been remarked that evidence had been forthcoming for the existence of nuclear-energy levels akin to the energy levels of the outer electrons. Owing to the fact that a neutron, like all primary particles, has a wave as well as a particulate nature, it may happen that the energy of a neutron—and hence its wavelength—is attuned to that of the nucleus, as a receiving set may be tuned to a wireless wave. One of the energy levels of the nucleus was apparently 'tuned' for the reception of 25-volt neutrons. This absorption of neutrons over a quite critical range actually results in the reaction described at the beginning of the chapter, for the isotope of mass 239 formed by neutron capture decays (half-life 25 minutes) to form element 93. This

element 93, named neptunium, is also unstable (half-life 2½ days), and emits a further electron to form the stable element of number 94, plutonium (Fig. 18):

$$
\underset{}{{}^{238}_{92}U} + {}^{1}_{0}n \longrightarrow \underset{\text{highly unstable}}{{}^{239}_{92}U} \longrightarrow \underset{\text{unstable}}{{}^{239}_{93}Np} + \beta^{-} \longrightarrow \underset{\substack{\text{feebly}\\ \text{radioactive}}}{{}^{239}_{94}Pu} + \beta^{-}
$$

This reaction will be considered later.

'*U* 235'

While the presence of the absorption band explained the behaviour of 25-volt neutrons, it did not explain the entirely different phenomenon of nuclear fission. Niels Bohr, whose quantum theory of the atom was described in Chapter II, suggested an explanation which has since been proved right. He ascribed the radioactivity obtained with thermal neutrons to the presence of another isotope of uranium, one of mass 235. The isotope is present to the extent of only seven parts per thousand of the normal element, and, owing to its small abundance and the difficulty of resolving the mass lines of very heavy elements in the mass spectrograph, had not been discovered until comparatively recently. According to Bohr, fission with thermal neutrons occurred only in the 235 isotope. Fission of 238 could occur, but only to an appreciable extent when energies of upward of a million e.v. were used.

Nature of Nuclear Forces

Present-day ideas of nuclear structure are based on the assumption that atomic nuclei are composed of protons and neutrons held together by forces which are extremely powerful at very short distances, but fall off rapidly as the particles separate. These nuclear binding forces have to compete with electrostatic repulsive forces between the protons in the nucleus, which, carrying positive charges, repel like

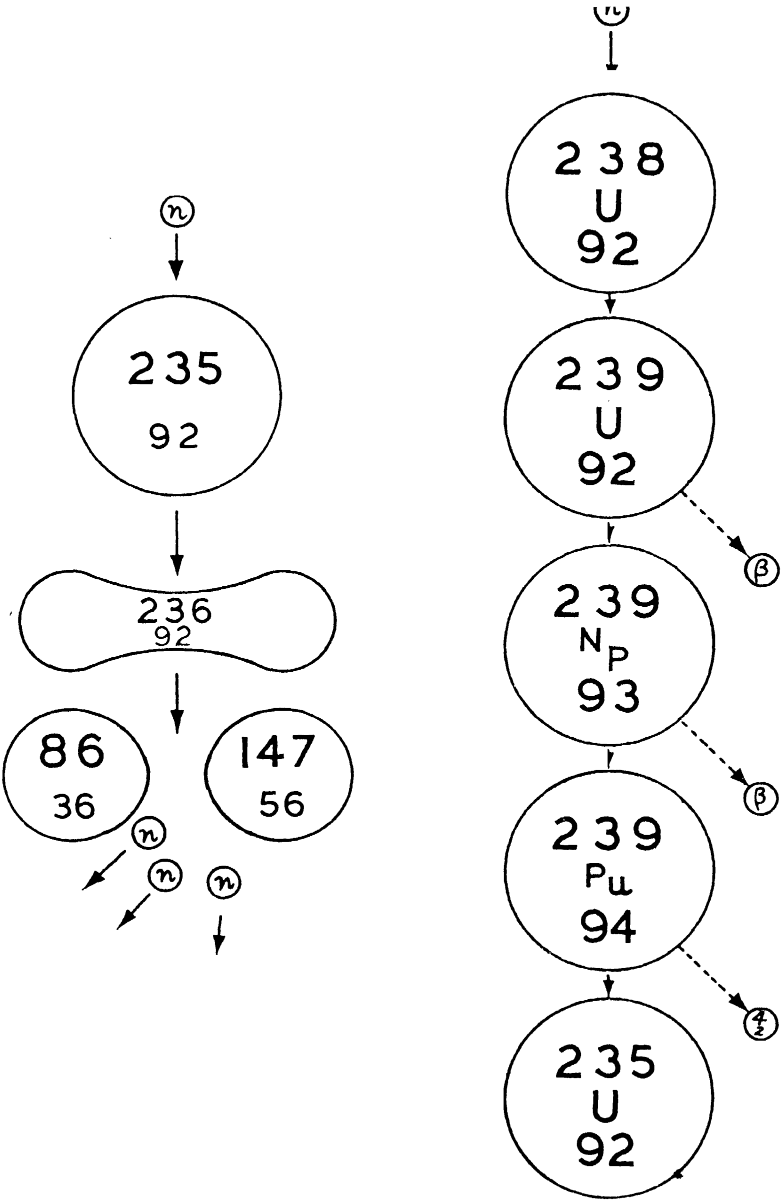


FIG. 18. NEUTRON CAPTURE BY URANIUM NUCLEI

(*Left*) Fission of U 235 follows absorption of a neutron. The fission products are not always krypton (36) and barium (56), as shown.

(*Right*) Decay of U 238 follows absorption of a neutron. The plutonium so formed decays naturally to the 235 isotope of uranium by emission of alpha particles. (Half-life, 10,000 years.)

element 93, named neptunium, is also unstable (half-life $2\frac{1}{2}$ days), and emits a further electron to form the stable element of number 94, plutonium (Fig. 18):

$$\underset{}{{}^{238}_{92}\mathrm{U}} + {}^{1}_{0}n \longrightarrow \underset{\text{highly unstable}}{{}^{239}_{92}\mathrm{U}} \longrightarrow \underset{\text{unstable}}{{}^{239}_{93}\mathrm{Np}} + \beta^{-} \longrightarrow \underset{\substack{\text{feebly}\\ \text{radioactive}}}{{}^{239}_{94}\mathrm{Pu}} + \beta^{-}.$$

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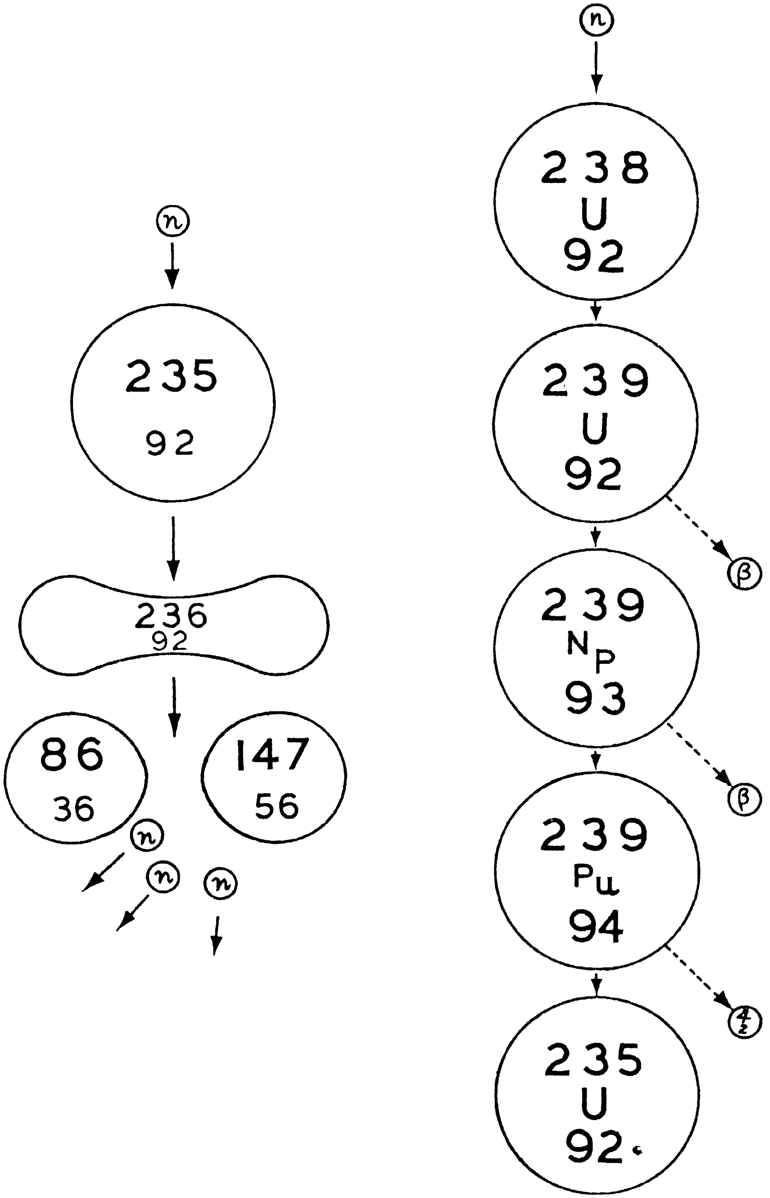

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nucleus. Meitner and Frisch likened the nucleus to a liquid drop, which is rendered unstable by the presence of an electrical charge. Using this model, Bohr and Wheeler showed that the nucleus would have a critical energy for stability. When a neutron or other 'packet' of energy is added to it the critical state may be exceeded, and the nucleus then divides into two smaller portions and a number of neutrons. The potential energy of nuclear distortion is converted into kinetic energy of separation, and the fission products, including neutrons, fly apart at high speed. These authors deduced that not only neutrons but sufficiently energetic gamma rays, protons, and deuterons would also accomplish fission.

On the basis of their theory they also calculated the likelihood of capture by a heavy nucleus of neutrons of varying energies. This sounds rather recondite, but it is a most important point when one is considering whether the fission reaction will be self-maintaining. Obviously if the likelihood of capture were very small, then fissions would be very rare —the neutron would be more likely to pass out of the system altogether.

The upshot of their calculations was that ${}^{235}_{92}U$ should capture neutrons of all energies with high efficiency and undergo fission, whereas ${}^{238}_{92}U$, and ${}^{232}_{90}Th$ (thorium has one isotope only), and ${}^{231}_{91}Pa$ (protoactinium, a very rare element, and for that reason of no interest in this present discussion) should be much less effective in capturing neutrons of thermal energies, and should in any event undergo fission with fast neutrons only (Fig. 18).

Another interesting conclusion was that plutonium ${}^{239}_{94}Pu$ should be capable of undergoing fission in a manner similar to U 235. (U 235 will be used from now on to designate that somewhat notorious material ${}^{235}_{92}U$.)

It was by 1939 generally realized that nuclear fission repre-

sented a likely method of utilizing atomic energy on an industrial scale, and for military purposes also.

Nevertheless, there were many difficulties to be overcome before this could be achieved. The Bohr-Wheeler theory showed that the 'capture cross-section'—*i.e.*, efficiency of absorption of neutrons by U 235 and by plutonium—was high, so that neutrons emitted in fission would readily be absorbed by further nuclei, but—and there was not one but several 'buts.' . . .

It must be remembered that the dimensions of the nuclei are exceedingly minute (even if at times they behave as if their cross-sections are thousands of times greater than their nominal value). Neutrons released by fission are therefore likely to miss these nuclei altogether and eventually escape into the air, away from the seat of the reaction. This happens on bombardment of ordinary uranium by neutrons, because the U 235 nuclei are present, as we have seen, to the extent of only 0·7 per cent. of the whole; and therefore the greater part of the projected neutrons, and of those produced in fission by a small number of collisions, are carried away from the target, and take no part in causing further fission. The ${}^{238}_{92}U$, which forms practically 99·3 per cent. (the 234 isotope is present to the extent of only 0·006 per cent.) of the whole, is, as just indicated, less efficient in absorbing neutrons. When it does so it is as likely as not to emit gamma radiation and form ${}^{239}_{92}U$, which decays to neptunium and plutonium. Neutrons absorbed in this way are wasted as far as fission is concerned, for only this latter process is self-maintaining.

Self-maintaining Chain Reaction

The problem, then, was either to separate U 235 from the main bulk of U 238 of identical chemical property, or to

devise some means of producing in quantity the plutonium formed in thus far unseeable and unweighable quantities by neutron capture in the heavier isotope. Either alternative presented immense difficulties; at the time they were first envisaged it was not certain that, even if accomplished, the ultimate purpose of their preparation would be served—yet both methods have been brought to a successful outcome.

It will be recalled that the fission of a 235 nucleus following neutron capture results in the liberation of fragments of the parent nucleus in the form of nuclei of lower atomic number and also of further neutrons, thus suggesting the possibility of a chain reaction, with a snowball effect and the liberation of 170 M.e.v. of energy for each nucleus shattered. Obviously, for such a reaction to be sustained, there must be at least as many neutrons produced in unit time as disappear either by reaction or because their motion carries them away from the reaction zone. It is impossible, of course, to confine neutrons in any container, for, as we have seen, only head-on collisions with heavier nuclei will reflect them back from the walls. But, since nuclei are only about one hundred millionth of the cross-sectional area of atoms, such collisions happen comparatively infrequently. It is necessary, therefore, to make the mass of reacting material of such a size that any neutrons produced stand a high chance of eventual collision and capture. Since, as may readily be shown, a sphere has less area for the volume it encloses than any other figure, it is the most suitable shape to use in order to conserve neutrons. The number of these particles produced will be proportional to the number of fissions and hence of nuclei, and will therefore depend on the volume of material, whereas the number that escape will be proportional to the surface through which escape may take place. Hence efficiency dictates a spherical form for the reacting material.

The minimum size which the sphere must have in order that the reaction may proceed will also depend on the effective cross-section for capture exhibited by the isotope. This in turn varies with the speed of the neutron in a manner calculable from Bohr and Wheeler's theory.

Explosive Release of Energy by Fast Neutrons

Peierls and, independently, Chadwick and Frisch pointed out early in 1940 that on the basis of this theory a comparatively small quantity of the pure, or nearly pure, 235 isotope would be sufficient to enable a fast-neutron chain reaction to take place. About 1 per cent. of the neutrons are formed from the fission elements with a delay of one-hundredth of a second, and about 0·1 per cent. with a delay of roughly one minute. (This phenomenon is used, as explained in the Smyth *Report on Atomic Energy*, to control the atomic pile.) Furthermore, since most of the neutrons are produced on fission without any delay, are released at a very high speed, and react with great rapidity, the interval between successive steps in this branching chain will be of the order of 10^{-12} second. This means that energy will be released at a rate in excess of anything previously contrived by man. There must result, as a consequence, an explosion of the most stupendous magnitude.

The feasibility of an atomic bomb as outlined above depends on a reaction involving fast neutrons—that is, of neutron energies 1 M.e.v. and more. It has been seen that neutrons, in virtue of their lack of charge, are able to penetrate U 235 nuclei without hindrance, liberating energy and further neutrons. It may be asked, Why do not the fission fragments themselves break down further nuclei, since they are ejected with prodigious force? The answer to this is that they carry high nuclear charges themselves—40

to 60 units or so—and are repelled on approaching a uranium nucleus which carries 92 charges. This repulsion is proportional to the square of the product of the charges of the colliding particles, and to their masses. A proton requires an energy of 10 M.e.v. before it can surmount the uranium barrier, and a fission fragment of charge 50 and mass 100 will require 250,000 times this. But the combined energy of ejection of both fission fragments and the three neutrons is *only* 170 M.e.v., so that even allowing for the quantum tunnel effect the chance of disruption is negligible: neutrons form the essential links in the chain of propagation.

Controlled Release of Energy by Slow Neutrons

It has already been mentioned that slow, or thermal, neutrons are even more effective than faster ones in promoting fission, and the initiation of a chain reaction by such means has been considered. In order to slow down fission neutrons to ordinary thermal energies it is necessary to provide, as we have already seen, a supply of nuclei of small mass such as hydrogen, helium, or carbon, to mention a few of the lighter elements of the periodic system. Helium, being gaseous at room temperature and forming no chemical compounds whatever, is unsuitable as a slowing-down medium, since the concentration of such nuclei in a given volume is necessarily small. Hydrogen, in combination with oxygen, which is of not too high a mass, seems the most obvious choice; but here a difficulty is at once apparent, for hydrogen absorbs neutrons appreciably, which is, of course, fatal to the continuance of the chain reaction. The isotope of hydrogen, mass 2—deuterium—is free from this objection, and so is oxygen. Hence deuterium oxide, or heavy water, forms the most suitable medium for the process. Having reached thermal energies, the neutrons

will be jostled about between the deuterium and oxygen nuclei until eventually colliding with a U 235 nucleus, when fission will take place (elastic scattering is also possible, but sooner or later absorption will occur). As before, there is a critical minimum size to enable the reaction to proceed, depending on the concentration of the isotope and the escape surface for the neutrons. Rough calculation shows that the time elapsing between the emission of a neutron and its slowing down and subsequent capture will be at least several ten-thousandths of a second. This time lag, occurring at each stage in the chain of fissions, precludes the onset of a reaction of such catastrophic proportions as may occur in the fast neutron process; for although an explosive reaction *could* occur, it would happen before an appreciable part of the U 235 had decomposed. The reactants would separate, therefore, and the critical conditions for continuance, under which neutron production by fission is at least equal to loss by absorption plus loss by outward diffusion, would no longer be fulfilled.

The slow-neutron reaction has therefore great promise as a method of controlling the liberation of atomic energy. Several neutrons are emitted per fission, and if all of them succeed in causing further fissions a rapidly diverging energy-producing chain must result. It was realized as far back as 1939 that the slow-neutron reaction in U 235 provided a likely method of controlling the liberation of atomic energy, but what was not clear at the time was to what extent, if any, it would be necessary to concentrate this isotope before the reaction could proceed.

Slow neutrons, it was believed, reacted almost entirely with U 235, but to some extent with U 238; and since this latter isotope constituted nearly 100 per cent. of the whole it was open to question whether the self-maintaining fission process could be made to work in the naturally occurring

element. The Halban-Joliot-Kowarski experiment suggested that this was likely. In their experiment a radon-beryllium source of neutrons was placed at the centre of a large volume of water in which was dissolved a uranium salt, and the intensity of the neutrons transmitted through this solution was measured. As a consequence of absorption by hydrogen (from the water) and by uranium there was, of course, a considerable drop in neutron intensity. A similar experiment was then performed with the uranium omitted. This might be expected to have resulted in a greater yield of neutrons in the recording instrument, owing to the absence of the absorbing uranium. In fact there were rather less. The inference was that the uranium actually produced more neutrons than it absorbed, and calculations gave 3 as the number of neutrons emitted per fission.

These investigators perceived that if the hydrogen of water could be replaced by the non-absorbing deuterium it might be possible to devise a self-sustaining reaction without concentrating the isotope in any way. The necessary condition for this to be feasible was that the dimensions of the apparatus should be large enough to limit the neutron loss at the boundary to the amount formed in the bulk of the system; and this, it was calculated, required a comparatively vast quantity—several tons, in fact—of heavy water. As has been mentioned in the British Government statement, to give decisive evidence concerning this possibility the experiment required almost the entire world stock of heavy water—165 litres—obtained from the Norsk Hydro Company of Norway. Before the work could be completed the German invasion of France took place. Professor Joliot dispatched his two associates to Britain, where the work was continued at Cambridge, and the feasibility of a self-sustaining chain reaction demonstrated.

Although this sequence of changes does not proceed at

the pace of the fast-neutron reaction, it must still accelerate to a point where it becomes unworkably hot and possibly explosive if neutrons are being generated faster than they can be dispelled, or cease altogether if the rate of generation is less than the critical value. This critical rate depends on the uranium content, which changes continually as disintegration proceeds, and therefore to control the process it is necessary to provide some regulating mechanism. Adler and von Halban suggested that the metal cadmium could be utilized for the purpose. Whereas the absorption of neutrons by uranium is practically independent of temperature over the range concerned, absorption by cadmium actually increases rapidly for small rises in temperature. Consequently the fission energy, which appears as heat in the system and causes a rise in temperature, will result also in an increased absorption of neutrons by the cadmium, with a consequent reduction in the number available for furthering fission. The reaction will tend to adjust itself to a temperature where absorption by uranium plus cadmium and loss from the system by diffusion is equal to the rate of production by fission.

The Atomic Pile

The next contribution came from Fermi, in Chicago, who introduced carbon in the form of graphite as the moderating material. This has the advantage of being cheaper and more readily available than heavy water, but the disadvantage of a high neutron absorption. Fortunately, however, it was discovered that absorption was due in large measure to the presence of small traces of impurities, and, by a reduction of these neutron capture was also reduced to the point where the reaction could proceed. Nevertheless, a most stringent specification had to be enforced, one which, as described in the official U.S. report, represented the extreme limit to

which an industrial product could conform. Owing to the high capacity for neutron absorption by boron this element could not be permitted as an impurity to an extent of more than one part per million.

This 'atomic pile' of Fermi (see Fig. 19) differed from the preceding arrangement in one other main respect—namely, that the uranium was introduced in the form of metallic rods, and not dissolved in the moderant. This modification has an important bearing on the efficiency of the process. Neutrons expelled by fission from a U 235 nucleus surrounded by heavy water take a certain time to lose thei velocity and reach thermal levels. During this time their chance of capture by U 238 nuclei, present in great abundance in their vicinity, is very high, so that most of them will be removed by this means, and so will not be available for producing fission in the lighter isotope. But if the metal is in the form of rods separated by about fifteen inches of graphite or a less distance of heavy water, then the high-velocity fission neutrons which escape from the uranium metal into the moderant will slow down and drop below the resonance-capture levels of U 238. Therefore, on entering the next 'slug' of uranium they will react almost entirely with U 235. By this means the neutrons used up in absorption by U 238 (a reaction which leads eventually to the production of plutonium) and also by the moderant and its impurities, together with the neutrons lost by escape from the system plus the neutrons required for fission, are made to balance the neutron supply resulting from that fission. As a further step in husbanding the neutron supply the rods are arranged in a manner calculated to intercept these particles in the most effective manner.

The most suitable shape for such a pile is, from the standpoint of neutron conservation, a sphere, and the first system was built in this shape. Before it was finished the reaction

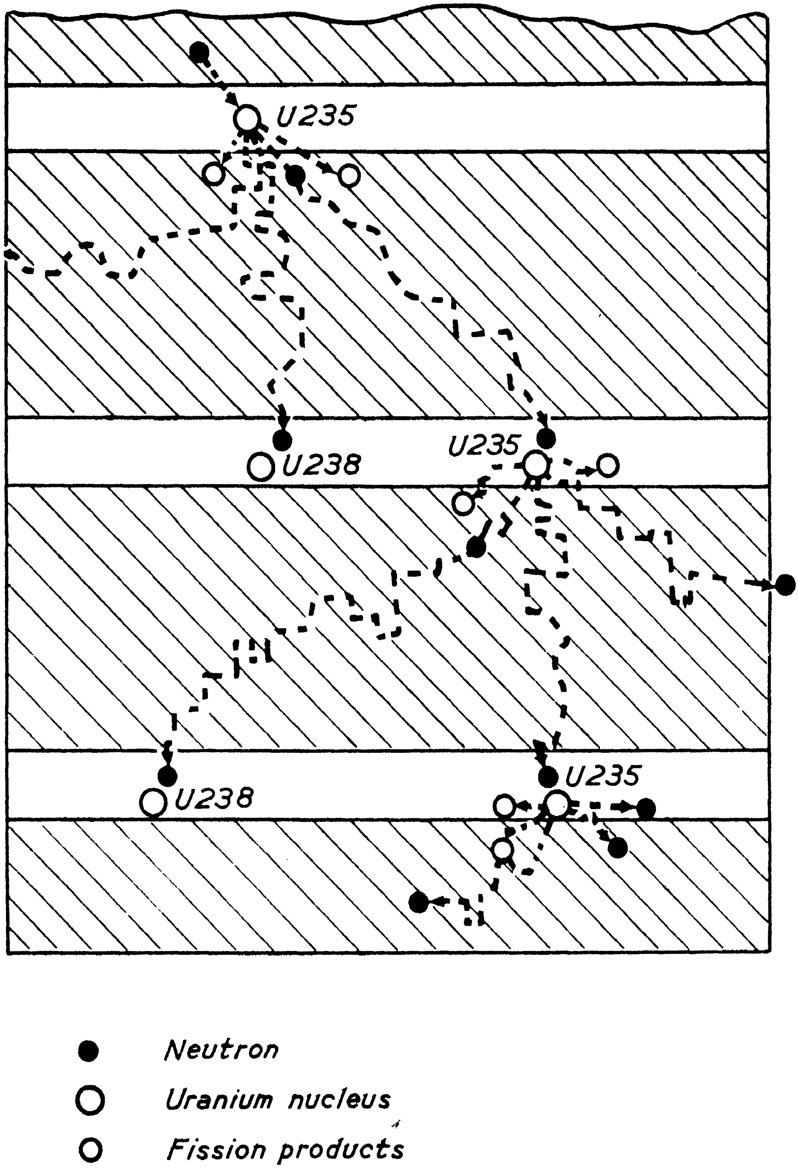

FIG. 19. SCHEMATIC OUTLINE OF THE ATOMIC PILE

Neutrons reacting with U 238 nuclei produce plutonium, but do not liberate neutrons.

was found to be self-sustaining, and therefore the topmost layers were omitted. Control was effected by means of boron, present as boron steel, which could be inserted or withdrawn from the pile at will. On December 2, 1942, the first atomic pile commenced operation, with uranium metal containing only its normal content of U 235. At first, by means of the boron absorbers, the reaction was limited to a power output of half a watt, but a few days later this was raised to 200 watts.

The primary object of this work was not, of course, to harness atomic power in a controlled manner, but to produce plutonium for atomic bombs. For plutonium to be produced in quantity required a prodigious neutron supply, only obtainable from this self-perpetuating chain reaction, and the power or heat production of the pile was incidental. The feasibility of the method having been demonstrated, and theoretical calculation thus confirmed, it was then necessary to build a pile to give an output of 1000 kilowatt-days per gram of plutonium required. Now the minimum size for an effective atomic bomb has been shown by experience to be about four kilograms, so that to produce one bomb per week, the plant would need to work continuously with a power rating of roughly 600,000 kilowatts. A fair-sized generating station feeding the grid system in Britain produces power at the rate of 100,000 kilowatts, which gives an indication of the magnitude of the project.

Such a pile was constructed at Hanford, in the state of Washington.

To dissipate the heat produced during the running of the plant, water cooling was employed, and the temperature of the pile did not, as a consequence, much exceed 100° C. Cooling necessitated the incorporation of a circulating system in the structure, leading to some loss in efficiency due to further unproductive neutron absorption; but by a slight

increase in the size of the pile (and a consequent reduction in the *fraction* of the total neutrons which could escape over the boundary) this was compensated.

Before we leave the plutonium project some reference should be made to the radioactive elements which result from the fission of U 235. Included in these products are intensely active isotopes of the gases xenon, krypton, and bromine, and during the fission of 1 lb. of U 235 several ounces of these substances are released. They exert a disintegrating effect on the metal of the slugs if the latter is in the cast state, so that powdered metal has advantages. A much more serious drawback is the danger to life of their emanations; their presence necessitates elaborate shielding of the pile and remote control of all operations, including those of changing the slugs and extracting (by purely chemical means) the small quantities of plutonium produced. The method finally adopted to get rid of these products was to release them into the atmosphere by means of a tall stack. This was not too great a hazard, because most of the radioactivity decays within a few weeks to zero value. The solid fission products were disposed of underground.. They could not be released into the atmosphere owing to the danger of settling on the ground in appreciable concentration.

This short outline of the atomic-pile method of utilizing nuclear energy gives no idea of the immense magnitude of the venture. For a comprehensive account of all the technical details which have been released publicly the reader will naturally consult the official U.S. publication *Atomic Energy*, published in Great Britain by H.M. Stationery Office.

Energy of the Fission Process

It is appropriate at this stage to consider the magnitude of the energy changes involved in nuclear-fission processes.

U 235 will be taken for the purpose of illustration, the corresponding values for plutonium being of the same order of magnitude.

It has been stated that the U 235 nucleus liberates 170 million electron-volts of energy as a result of its splitting. A better idea of the potentialities of such an amount may be obtained by comparing the energy obtainable from nuclear sources with that made available by the more familiar electronic rearrangements of the outer shell of the atom—in other words, of an ordinary chemical reaction such as combustion.

The heating power—or, to express ourselves more technically, the calorific value—of 1 lb. of good-quality coal is about 13,000 British thermal units—B.Th.U., for short. A pound of coal when burnt in air will therefore produce enough heat to raise 13,000 lb. of water one degree Fahrenheit. If this is expressed in the units used in pure science it amounts to three and a quarter million gram calories, where the calorie is the amount of heat required to raise 1 gram of water through 1 degree centigrade. Actual experiments in which heat has been used to produce mechanical motion have shown that the calorie is equal to 42 million ergs (see p. 45 for a definition of this quantity). Thus 1 lb. of coal liberates on combustion:

$$3\tfrac{1}{4} \times 10^6 \times 42 \times 10^6 = 1{\cdot}36 \times 10^{14} \text{ ergs.}$$

One electron-volt of energy is equal to $1{\cdot}6 \times 10^{-12}$ erg, so that:

$$\begin{aligned} 170 \text{ million e.v.} &= 170 \times 10^6 \times 1{\cdot}6 \times 10^{-12} \\ &= 2{\cdot}7 \times 10^{-4} \text{ erg.} \end{aligned}$$

This quantity is liberated by one single U 235 nucleus, which in weight may be taken as equal to that of the U 235 atom, the weight of the external electrons being negligible.

The weight of the proton is $1{\cdot}67 \times 10^{-24}$ gram. Hence

the weight of an uranium atom is $235 \times 1{\cdot}67 \times 10^{-24}$ gram. This weight of uranium produces $2{\cdot}7 \times 10^{-4}$ erg, so that one gram of uranium will produce:

$$\frac{2{\cdot}7 \times 10^{-4}}{235 \times 1{\cdot}67 \times 10^{-24}} = 6{\cdot}8 \times 10^{17} \text{ ergs.}$$

Comparing this quantity with the amount of energy liberated by 1 lb. of coal, we see that the nuclear fission of 1 gram of uranium 235 is energetically equivalent to:

$$\frac{6{\cdot}8 \times 10^{17}}{1{\cdot}36 \times 10^{14}} = 6000 \text{ lb. of coal.}$$

Thus 1 lb. (453 grams) of U 235 would produce as much heat as, roughly, 1200 tons of good-quality coal. This is a low estimate, for it does not include the heat liberated on subsequent decay of the fission fragments.

This heat, of course, comes from the mass defect of the total fission products compared with the mass of the parent nucleus. If 1 gram of U 235 were completely annihilated, the energy produced, from Einstein's equation (p. 45), would be:

$$1 \times (3 \times 10^{10})^2 = 9 \times 10^{20} \text{ ergs.}$$

The energy actually liberated is only $\dfrac{6{\cdot}8 \times 10^{17}}{9 \times 10^{20}}$ of this, so that only $0{\cdot}75 \times 10^{-3}$—*i.e.*, less than one part per thousand—of the mass disappears!

Separation of Isotopes

The success of the U 235 atom bomb depends, as previously stated, on the almost complete separation of the 235 constituent of the uranium from the 238 constituent, which forms the main bulk of the element.

This problem of isotope separation is not new to science.

We have already seen that a complete separation of the isotopes of hydrogen had been made by an electrolytic method as early as 1932, and the history of the subject dates back to 1913, when Aston effected a partial separation of the isotopes of neon (masses 20 and 22) by fractional diffusion through a pipeclay tube. Success in the isolation of deuterium had stimulated interest in such work, and considerable advances in technique were made during the next seven years. Nevertheless, there was an immense gulf to bridge before the separation of the isotopes of uranium could be effected, for the ease of separation is related to the relative masses of the constituents. The mass-ratio deuterium: hydrogen is 2:1—the highest known ratio of any isotopes—and as a consequence this separation was the easiest of all to effect. Uranium, being the heaviest of the elements, presented the most difficult problem of all, and there were a number of other factors which added to the difficulty. These we shall notice later; but first, to obtain a background to the subject, it would be desirable to consider more generally the nature of the task and the means available for accomplishing it.

Isotopes, then, are substances whose atoms differ in mass but have the same chemical properties. This identity of chemical behaviour arises from the fact that the positive charges on the nuclei of isotopic atoms are identical, and hence there are the same number of planetary electrons arranged in the same manner (or the charge-density distribution is the same for each, in wave-mechanical parlance) around each nucleus. Since the chemical properties depend only on the outer (or 'valency') electrons they will be the same for the various isotopes (though minute differences in the chemical properties of isotopes of very light elements have been detected).

The most obvious method of separation would seem to

be that by means of which the complex nature of elements was first shown: to wit, the mass spectrograph. This instrument is undoubtedly capable of effecting a complete separation, although here again the heavier elements are more difficult to resolve than the lighter ones. But with a sufficiently high voltage and magnetic field uranium can be separated almost completely into the 235 and 238 fractions, and, less efficiently, the 234 fraction may be concentrated. It was by this means that Bohr's suggestion of slow-neutron fission being due to the 235 isotope was experimentally confirmed.

When small quantities of U 235 and U 238 collected by this means were subjected to an intense slow-neutron bombardment no fission was observed in the U 238, but was found to a considerable degree with the lighter fraction.

The difficulty with this method lies in the smallness of the quantities which may be separated, for normally ion currents of a few hundred millionths of an ampere are used. In recent years specially designed instruments have been made in which currents ten thousand times this value have been obtained. The ions were produced at a plane surface of large area. Quantities of several milligrams of the potassium isotopes 39, 40, and 41 have been obtained by means of prolonged running of the apparatus.

Separation by Means of the Cyclotron

An extension of the method is to use the cyclotron for separation. This is, in effect, a large-scale mass spectrograph of high resolving power. By using an extended ion source to provide a large current, and an internal target on which to collect the sample, it is possible to deal in currents of many milliamperes and obtain separations of uranium isotopes greater by a factor of many thousands than is usual.

This method then becomes a possible means of separating U 235 either completely or, in greater quantity, partially.

The great difficulty which had to be overcome before this method could be made to yield isotopes in practicable amounts was associated with what is known as the space charge of the ions. The beam which is accelerated in the cyclotron consists of particles all carrying electrical charges of the same sign—positive ions, in fact. It is by virtue of this charge that they respond to the electrical and magnetic fields of the instrument (the neutron, for example, cannot be accelerated in the cyclotron or any other instrument, because of its lack of charge). But these charges also act upon one another, and set up a mutual repulsion of all the particles in the beam. Consequently, when an attempt is made to increase the density of ions in the beam considerable spreading and lack of focusing result. Therefore, if two or more isotopes are present their paths will overlap, and they cannot then be resolved into separate constituents.

Lawrence saw that the way to overcome the difficulty was to ionize the residual gas in the cyclotron. This produced large numbers of electrons which moved in small spirals in the powerful magnetic field and to a considerable extent annulled the mutual repulsion of the ions in the beam and prevented its divergence. He was therefore able to separate quantities of a much greater order of magnitude than had previously been accomplished. The specially designed cyclotron used for this purpose has been designated the 'calutron'—a condensation of California University Cyclotron. It was found more economical to effect only partial separation of U 235 and U 238 in a single operation, since thereby greater quantities of the material could be manipulated. Also, by the use of a series of ion sources and targets, each working independently, but housed between the same magnet, one cyclotron could be made to do the work of

several. A considerable saving in time and expense was effected by starting with a uranium sample already partially enriched in U 235 by a method which we shall next consider. The calutron method of separation is unquestionably the most efficient and compact of all those depending on actual separation of the isotopes, and, although given little space in the U.S. statement, represents the most interesting aspect of all the atomic-energy researches which have been accomplished. Although a considerable amount of electrical energy is used up in the process, it can be replaced quite readily from the enriched isotope, when suitably harnessed, and still leave some energy available for other purposes. The harnessing of the enriched isotope is a much simpler matter than the harnessing of that of natural concentration. Not merely is the apparatus more compact (a much greater loss of neutrons may be permitted), but there is no necessity for the same rigid specification for impurities. However, it cannot be said that the energy made available by the gain in concentration starting from *normal* uranium outweighs the cost of the process, for high yields cannot be obtained in such circumstances. A preliminary enrichment is first necessary, and this requires a considerable energy expenditure. Therefore the economic exploitation of atomic (or, rather, nuclear) energy has not yet been achieved—but the goal is well in sight.

Thermal Diffusion

Another technique which has received considerable attention, particularly in Germany, is that of thermal diffusion. In 1938 Clusius and Dickel achieved a quite sensational separation of the isotopes of chlorine by means of a very simple apparatus consisting of a vertical glass tube about 3 metres long and 1 centimetre in diameter, along the axis of which was extended a platinum wire (Fig. 20). Hydrogen-

chloride gas filled the intervening space, and the outer tube was kept at room temperature. When the wire was heated convection currents were set up, and the heated vapour rose along the surface of the wire to the top, then diffused outward to the side. On cooling it became denser, and sank gradually to the bottom. At the same time a continuous diffusion of hot gas took place from the wire directly outward to the tube, in which process the lighter atoms moved faster than the denser ones. As a consequence of convection and thermal diffusion the lighter constituent gradually gathered near the wire at the top, while the denser gathered near the wall at the bottom.

By using a sequence of such tubes in cascade Clusius and Dickel were able to effect a complete separation of the chlorine isotopes into masses of 35 and 37. Normally chlorine contains 25 per cent. of ^{37}Cl. This method is reasonably economical to operate under suitable conditions. To separate one gram of chlorine into its constituents requires approximately four thousand million calories, which gives an indication of what is considered reasonable in this context. Assuming electric power to be a halfpenny per unit, this would cost about £23.

The thermal-diffusion process shows to best advantage when the proportions of isotopes are comparable, so that the instance outlined above is one which is most favourable to the method. But the separation of U 235, which constitutes less than 1 per cent. of the parent substance, is much more difficult, quite apart from the fact that the mass ratio is also less. These disadvantages increase the cost of separation enormously. The energy required is estimated to be two-thirds of that liberated by the fission of the isotope.

Some advantage is gained by the diffusion being carried out on liquid uranium hexafluoride. Instead of a heated wire a tube is used, through which steam is passed. The

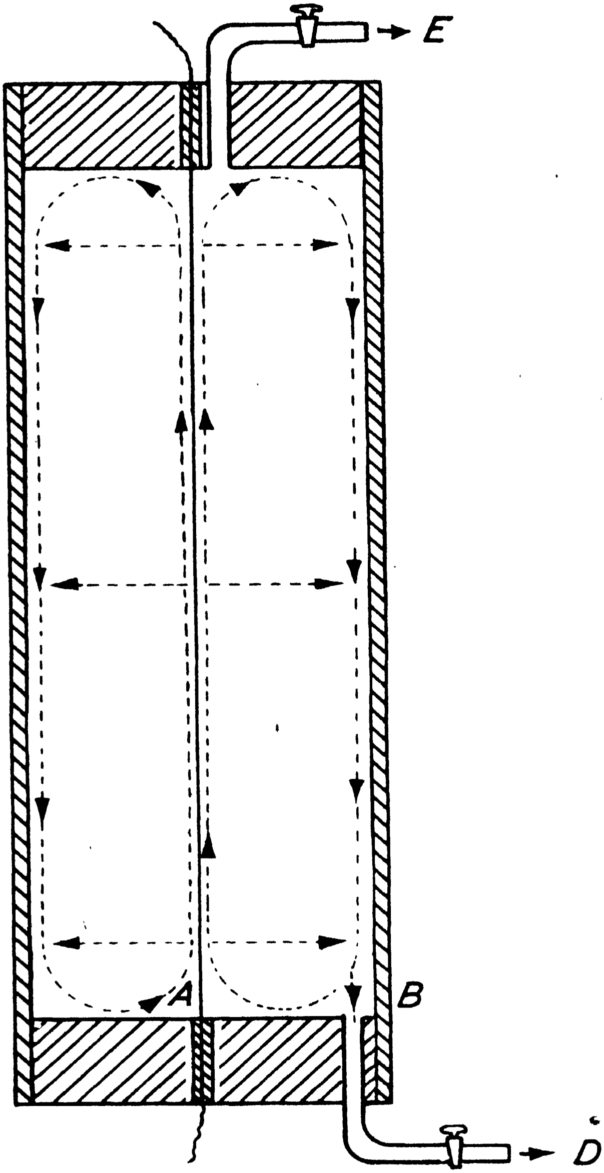

FIG. 20. CLUSIUS AND DICKEL'S THERMAL-DIFFUSION APPARATUS

The spiral *A* is either a heated wire, as shown, or a heated tube. The wall *B* is kept cool. The intervening space may be filled with either gas or liquid, which circulates in the manner shown. *D* is the outlet for the heavy fraction, and *E* for the light fraction. Many such units may be joined together in cascade, and successive enrichments obtained.

adjacent cold surface, consisting of another tube concentric with the first, is separated from the heated tube a distance of about $\frac{1}{25}$ inch. After equilibrium is reached the lighter fraction is drawn off at the top and the heavier at the bottom as before.

The most economical way of conducting the separation, it has been found, is partially to enrich the isotope by the Clusius and Dickel method and then use this enriched material either in the calutron or in the gaseous-diffusion apparatus, which we shall now describe.

Gaseous Diffusion

The separation of isotopes by gaseous diffusion is none other than the method used by Aston in his work on the isotopes of neon, reference to which has already been made (p. 61). This is the method that the British Government chose to adopt, for the reasons, as given in the British statement, that it was comparatively economical, its principles were well known, and its simplicity commended it for industrial exploitation.

According to the Kinetic Theory gases and vapours consist of minute particles (molecules) in rapid random motion and collision. The speed of this motion depends on, or manifests itself as, the temperature of the substance. As the temperature rises the average speed of the molecules increases. Now the velocities of these particles are not all the same, even for a pure gas consisting of a single isotope, but are distributed about the average velocity in a manner which can be calculated by a formula due to Maxwell. Thus, at any instant in a given volume of gas or vapour there are a few molecules with very low velocities and a few with very high velocities and an increasing number having various intermediate values, so that the curve representing number

of particles having a particular velocity is hump-shaped, as shown in Fig. 21.

When there is a mixture of two gases having different molecular masses, or two or more isotopic constituents, it follows from the Kinetic Theory that at the same temperature the average velocity of the heavier substance will be

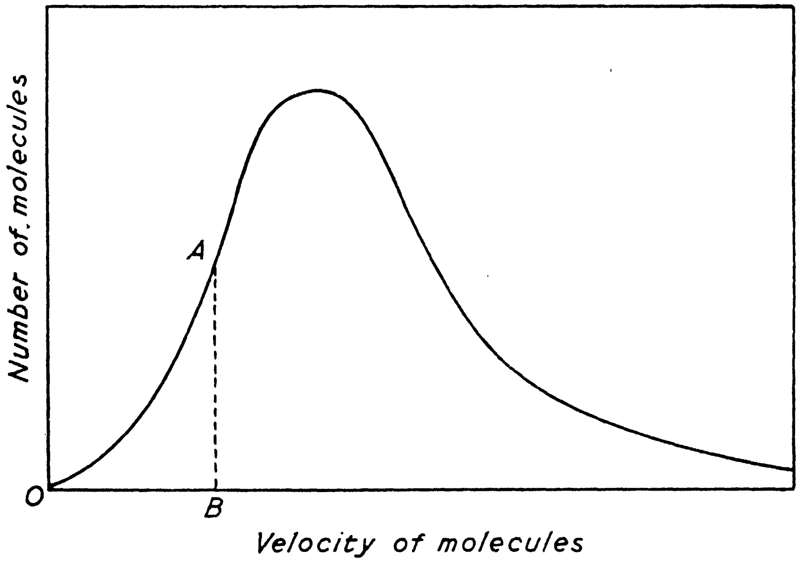

FIG. 21. MAXWELL'S DISTRIBUTION OF VELOCITIES IN A GAS

The gas as a whole is assumed still and its temperature uniform. But the individual atoms or molecules composing it are in a state of rapid motion. The height *AB* represents the number of particles having the velocity represented by *OB*.

less than that of the lighter. That property of a particle which scientists refer to as the kinetic energy is obtained by taking the product of half the mass (m) and the square of the velocity of motion (v):

$$\text{kinetic energy} = \tfrac{1}{2}\, mv^2.$$

For gaseous constituents of masses m_1 and m_2 and average

velocities v_1 and v_2, both at the same temperature, T, the Kinetic Theory states:

$$\tfrac{1}{2}\, m_1 v_1^2 = \tfrac{1}{2}\, m_2 v_2^2 = \text{constant} \times T.$$

From this it follows that if a gas consists of two isotopes of masses m_1 and m_2, where m_1 is heavier than m_2, the average velocity of the heavier isotope (v_1) will be *less than* the average velocity of the lighter isotope (v_2).

If such a mixture is confined within a container having a porous wall, whose pore diameter is comparable with the distance that the molecules move between collisions, it is possible for the faster molecules (lighter fraction) to pass through the pores more rapidly than the slower molecules. Since both species contain molecules of all speeds distributed about the mean value there will always be some of the heavier molecules moving faster than some of the lighter, and consequently such a porous wall will not affect a complete separation. But, on balance, the first fraction of gas which has been diffused will be slightly richer in the lighter fraction, and the remaining undiffused material will consequently be slightly richer in the heavier fraction. By this means mass difference may be utilized to effect separation. When the difference in mass is small it is necessary to carry out a most protracted succession of diffusions in order to obtain a measurable result, and, as will be seen from the equation just shown, the diffusion efficiency will depend on the ratios of the masses (actually on the square root of this quantity). Rearranging the previous equation:

$$\frac{v_2}{v_1} = \sqrt{\frac{m_1}{m_2}} = \sqrt{\frac{\text{lighter mass}}{\text{heavier mass}}}.$$

This method of gaseous diffusion has within recent years been exploited successfully by Hertz, who achieved an almost complete separation of the isotopes of carbon by the fractional diffusion of methane (CH_4). He employed a

succession of 48 fractioning units, of which one is shown in Fig. 22.

Now the gaseous diffusion of the uranium isotopes implies that the uranium can be produced in gaseous form. The

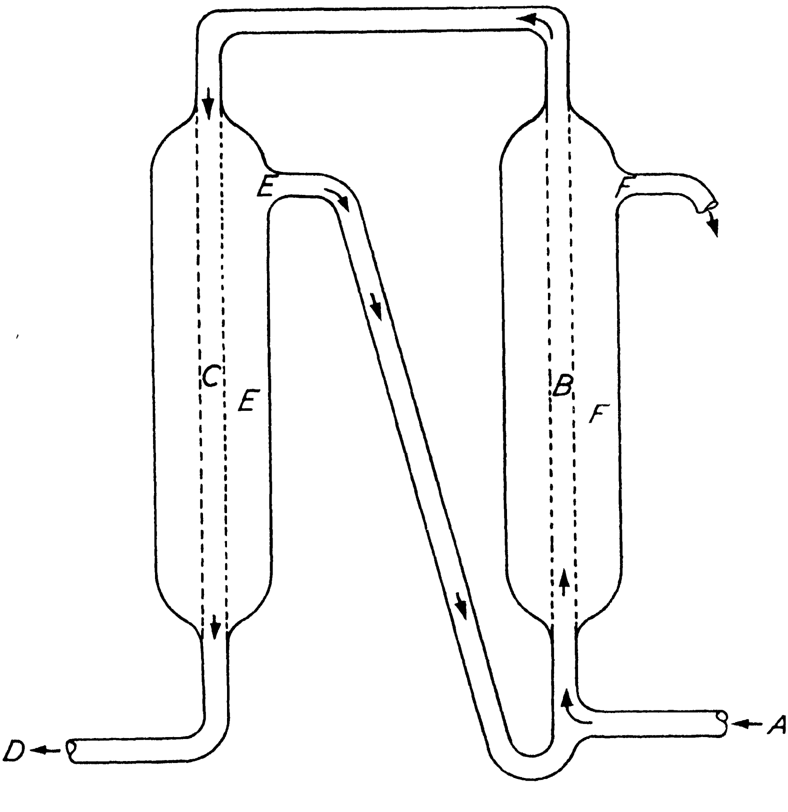

FIG. 22. THE HERTZ CYCLE FOR GASEOUS DIFFUSION

This diagram illustrates a unit forming part of a battery of 48 or more. Mixed gas enters at *A* from the following unit and passes along tube *B*, through the wall of which diffusion takes place. The heavier fraction passes on to tube *C*, where more of the lighter fraction is given up. The dense residue passes out at *D* to a preceding unit. Gas slightly enriched in the lighter fraction *E* passes back to *B* (via a pump not shown), and the still lighter fraction *F* passes on to the next unit.

element itself is a metal, the densest known, having a specific gravity of about 19. Also, it has an extremely high boiling-point, so that it is quite out of the question to carry out an elaborate diffusion on the metal vapour. Fortunately there is at least one chemical compound quite volatile at atmospheric temperature. This is uranium hexafluoride (UF_6).

The atomic weight of fluorine is 19, so that the molecule $^{238}UF_6$ has a weight of $238 + (6 \times 19) = 352$.
The molecular weight of $^{235}UF_6 = 235 + (6 \times 19) = 349$.
Hence the ratio:

$$\frac{\text{average speed of lighter molecule}}{\text{average speed of heavier molecule}} = \sqrt{\frac{352}{349}} = \frac{251}{250}$$

The difference is thus extremely small, only 1 part in 250, which necessitates a tremendous number of diffusion stages.

The central problem of this particular research was the production of a suitable diffusion barrier. For fractional diffusion to take place according to the equation just given it is essential that the pores through which the molecules pass should be not more than about one-tenth the 'mean free path'—*i.e.*, the distance between successive collisions—of the molecules. This mean free path decreases as the number of molecules in a given space increases—that is, as the pressure and density increase. But the amount of material separated increases with the pressure at which the process may be run. Therefore efficient separation in quantity dictates that the pore diameter should not exceed about one millionth of a centimetre. It was therefore necessary to design a barrier with the highest possible total area of pores, none or few of which exceeded this size. At the same time the barrier had to have sufficient mechanical strength to withstand a fair pressure across it—one atmosphere, or 15 lb. per square inch.

Quite apart from the minute enrichment at each stage

there are many other technical difficulties associated with uranium hexafluoride. One is that the substance is highly corrosive, and another that it is highly poisonous.

Its corrosiveness arises from the fact that it is a compound of fluorine, the most reactive of all elements, and is decomposed by water vapour to produce the almost equally reactive hydrogen fluoride (hydrofluoric acid). Since it is almost impossible to eradicate water vapour completely from a vast industrial plant it will be appreciated that even the insignificant theoretical gain at each stage of the diffusion may easily be reduced, or even obliterated, in practice.

Its extremely poisonous nature is also a very serious matter, especially since large quantities have to be handled. For this reason the whole of the plant has to be completely leak-proof.

Considering the difficulties associated with the process and the scale of operation—over four thousand diffusion operations are necessary in order to prepare 99 per cent. pure U 235—it is indeed a remarkable achievement, both scientifically and industrially, to have obtained by its means a successful isolation of the isotope.

The foregoing represents the chief methods which have been developed for separating isotopes. There are others, some of which have received brief notice in the U.S. report; but they are, for the moment at least, of less importance than those here described.

The Atomic Bomb

At the present time, naturally enough, interest in the exploitation of atomic energy centres around its most sensational aspect: the atomic bomb. From what the reader has already gathered in the preceding pages the general outline of the process will be apparent. An explosive release of

energy on an unprecedented scale will result from the setting up of a fast-neutron fission reaction, propagating as a diverging chain in pure or almost pure U 235, or plutonium. In order that the neutrons may build up it is necessary for them to be formed at a rate greater than they can be absorbed by fresh nuclei or escape from the system. This means that there is a certain critical minimum size below which the effect is inoperative. If, therefore, a spherical-shaped mass of metal is chosen for the bomb (in order to reduce the escape surface to a minimum for the amount of material enclosed) it will need to have a certain minimum diameter. Theory and experiment have shown this to be about 3 to 4 inches, and the mass of metal weighs approximately 8 lb. If the bomb is fabricated in the form of sections, then providing each of these falls somewhat short of the critical mass it is perfectly safe to handle. Only when they are brought together and the neutron reaction is initiated can an explosion ensue.

One simple way of initiating the neutron reaction is to introduce into the vicinity of the bomb a radon-beryllium source, which gives a copious supply of neutrons. It is not necessary, however, to do even this, for there is always present in the atmosphere a small supply of neutrons produced by the action of cosmic rays (see Chapter V). This neutron density is extremely small, although sufficient to set the spark to the gunpowder represented by the U 235.

Thus it is only required to bring the parts together for the reaction to ensue instantaneously. In the actual bomb mechanism it is therefore necessary to take extreme care that they are held apart to a safe distance until the time for their disintegration is ready. It might be supposed that if the bomb is surrounded with another sphere containing cadmium all the atmospheric neutrons will be absorbed. While this might be so, it happens that cosmic rays will

penetrate such a shield, and neutrons are likely to be created by chance within the uranium sphere. There is evidence that U 235 undergoes spontaneous fission with production of neutrons to a minute degree, and this may be due to cosmic-ray action. A shield cannot, therefore, give protection.

A consequence arising out of the presence of neutrons is that the reaction cannot be initiated at will once the critical size is exceeded. As the parts are brought together and neutrons, produced by a few odd fissions, escape from one section and find their way with little loss to the approaching sections, it is likely that a diverging fission reaction will begin before the parts are completely in contact. Once begun, and heat developed, the metal will vaporize with tremendous rapidity, and consequently expand. Expansion, apart from throwing out pieces of the reactants much below the critical size, will result in a mass of material whose surface has increased to such an extent that neutrons formed in fission will escape more readily than they can be produced. The reaction must therefore cease when perhaps only a fraction of the material available has decomposed. It is therefore essential to thrust these parts as close together as possible before reaction begins. The inertia (resistance to movement) of the material prevents instantaneous separation, and an extra millionth of a second of close proximity will mean that the diverging chain can branch much farther, for each link in the chain takes much less than one-millionth of a second for its completion. The efficiency of the reaction is further increased if the uranium is surrounded by a heavy metal to act as a neutron reflector. This serves the double purpose of increasing the inertia and delaying expansion. The device is known as a 'tamper.'

The actual mechanism for combining these pieces is a closely guarded secret. It is nevertheless a comparatively minor detail of engineering in no way fundamental to an

understanding of the subject. Probably the portions are brought together by some sort of propellant charge. This is one of the main factors determining the conversion of matter into energy within the bomb, and, together with the rate of evaporation and rate of chain branching, limits the amount of bomb material actually transformed.

Summary

The reader who has had the patience to digest the preceding narrative will now perceive that the hard-won position of a century and a half's labours may be summarized in a few minutes. Matter consists of 92 naturally occurring elementary kinds. Each of these elements is composed of myriads of minute particles called atoms, and the atoms of any element are, to a first approximation, identical. Atoms combine with one another, according to certain rules, to produce the infinite variety of substances of our experience. The atom has a structure. It consists of a central nucleus in which is concentrated almost the whole of the mass, and which in addition carries a positive charge of electricity. Surrounding the nucleus is a system of negative charges, or electrons, equal numerically to the nuclear charge. The nuclear charge, or atomic number, is always an integral multiple of the unit charge found on the lightest of all the elements—hydrogen. The electrons determine the chemical properties of the element, and since their number is equal to the nuclear charge (the atom as a whole being electrically neutral) this latter charge characterizes the element.

The mass of any nucleus is nearly an exact multiple of the mass of the hydrogen nucleus or proton, but in general falls slightly short of a whole number. Nuclei of all elements are believed to be built out of the same fundamental material —protons and neutrons, the latter having roughly the same

mass as the protons but no charge. The mass defect from a whole number is, according to relativity ideas, a measure of the energy released in the coalescence of these primary particles which form the nucleus, and gives, therefore, an indication of its stability. It is known that this mass *defect*, expressed as a fraction of the total number of particles concerned, decreases sharply from the lightest elements to the element of mass 16—oxygen—and then very gradually for elements of medium atomic numbers, eventually rising again as the nucleus grows in size. Mass numbers greater than 200 show a slight mass surplus compared with oxygen. This mass surplus indicates an excess energy, and is associated with a natural instability which manifests itself as radioactivity. A radioactive nucleus disintegrates with emission of particles and surplus energy in a manner not alterable by means ordinarily at our disposal.

Although an element is characterized by its atomic number, or total number of protons in the nucleus, its nuclear mass may vary within narrow limits owing to the association of a varying number of neutrons with the protons. Substances possessing the same nuclear charge, but having different mass numbers, are called isotopes. A particularly important isotope is that of hydrogen, having a mass of 2, known as deuterium. At the other end of the scale uranium, of atomic number 92, has three isotopes of masses 234, 235, and 238.

It has been found that almost all the elements can be made radioactive by bombardment of their nuclei with primary particles of sufficient energy to overcome the intense electrical repulsion caused by the nuclear charge, which thereupon suffer capture. The neutron, not being influenced by electrical charge, is exceptionally effective in initiating such changes. This induced activity consists for the most part of the emission of protons, neutrons, electrons, or helium

nuclei, but an unusual reaction may occur when neutrons are captured by the heaviest nuclei. Such heavy nuclei can divide into two approximately equal fragments with liberation of a vast amount of energy, and in addition several neutrons are ejected. The fact that the very particles which cause the energy liberation are regenerated or even multiplied enables, in certain circumstances, a self-propagating reaction to be maintained. The conditions for maintenance are that neutrons produced by fission shall be at least equal to those lost (*a*) by absorption, to cause further fissions, plus (*b*) unwanted or controlled absorption by non-neutron-producing nuclei, plus (*c*) escape of neutrons across the boundary of the system. If these conditions are fulfilled it is possible to use nuclear energy in a controlled manner by means of an atomic pile. If the pure isotope U 235 or the transuranic element plutonium is available in a pure or nearly pure state, then there is a critical size for this material, depending on the factors just enumerated, above which it is spontaneously explosible, with a violence hitherto not remotely approached.

NOTE ON THE INDUSTRIAL APPLICATION OF ATOMIC ENERGY

In order to utilize atomic energy for power production it is necessary to allow the pile to attain a high temperature, for only under such conditions is efficient conversion of the heat liberated in fission to mechanical effect possible. But one of the major difficulties in the operation of the pile is corrosion which arises from the great chemical reactivity of uranium. This necessitates encasing the uranium slugs in a material which is resistant to both chemical and nuclear attack and which, moreover, must be strong enough to withstand the pressure generated by the gaseous elements produced in fission. At temperatures of 500° C. or so these difficulties are considerably enhanced, but it is expected that they will be largely overcome within the next few years.

V

COSMIC RAYS AND THE MESON

Important scientific discoveries have frequently been made as a consequence of the investigation of some apparently trivial experimental discrepancy. The classic example is, perhaps, Ramsay's discovery of the inert gases argon, helium, etc., of the atmosphere, following an observed small difference in the density of nitrogen prepared from air compared with that obtained by heating a nitrogen-producing compound.

Discovery of Cosmic Rays

Another such instance led ultimately to the recognition of a weak but extremely penetrating radiation which appears to reach the earth equally from all directions of outer space. Concerning the origin and nature of this radiation very little is known, but evidence has accumulated, especially in recent years, to suggest that its investigation may well reveal the nature of the forces which bind the nucleus of the atom.

In the early years of this century several investigators drew attention to the fact that when an electric charge was imparted to a carefully insulated conductor the charge always leaked away, no matter what precautions were taken to prevent the leakage.

As an instance may be cited the behaviour of a charged electroscope. It may be recalled that this instrument consists merely of an insulated pair of gold leaves, which when charged are mutually repellent, and which when discharged

collapse into contact with each other (Fig. 23—(*a*) charged, (*b*) discharged).

When a charge is imparted to such an instrument, via the conducting plate, the leaves immediately diverge. If the instrument is now left the leaves will collapse very slowly; this indicates that the charge is being gradually neutralized. Now the only way in which neutralization can occur is for the air to be made conducting in some manner. At the time this phenomenon was being investigated radioactivity was very much 'in the air'—in more senses than one, apparently, for it was invoked to explain the production of ions (electricity carriers) in the atmosphere. It had been demonstrated that there is in every cubic foot of earth a minute amount of radioactive material which sends out radiation and, as a consequence, renders the air above slightly ionized. There is no doubt that some, at least, of the ionization is due to this cause, and most physicists were content to leave the matter at that.

But a few investigators felt that even after the effect due to minute traces of radio-elements had been eliminated there still remained a residual conductivity which awaited a satisfactory explanation. This belief was strengthened when it was found that a charged electroscope would leak even when kept over deep water many miles away from land. It would be expected that under such conditions any radioactivity due to the rocks on the sea-bed—even the most penetrating radiation—would be absorbed completely by a screen of water a mile or so deep.

A more significant discovery was soon to follow, however. The German physicist Gockel decided to explore the conductivity of the atmosphere at a much greater altitude than had hitherto been reached, and for this purpose assembled his instruments in a balloon and made several ascents, reaching an altitude of 13,000 feet or more. He discovered

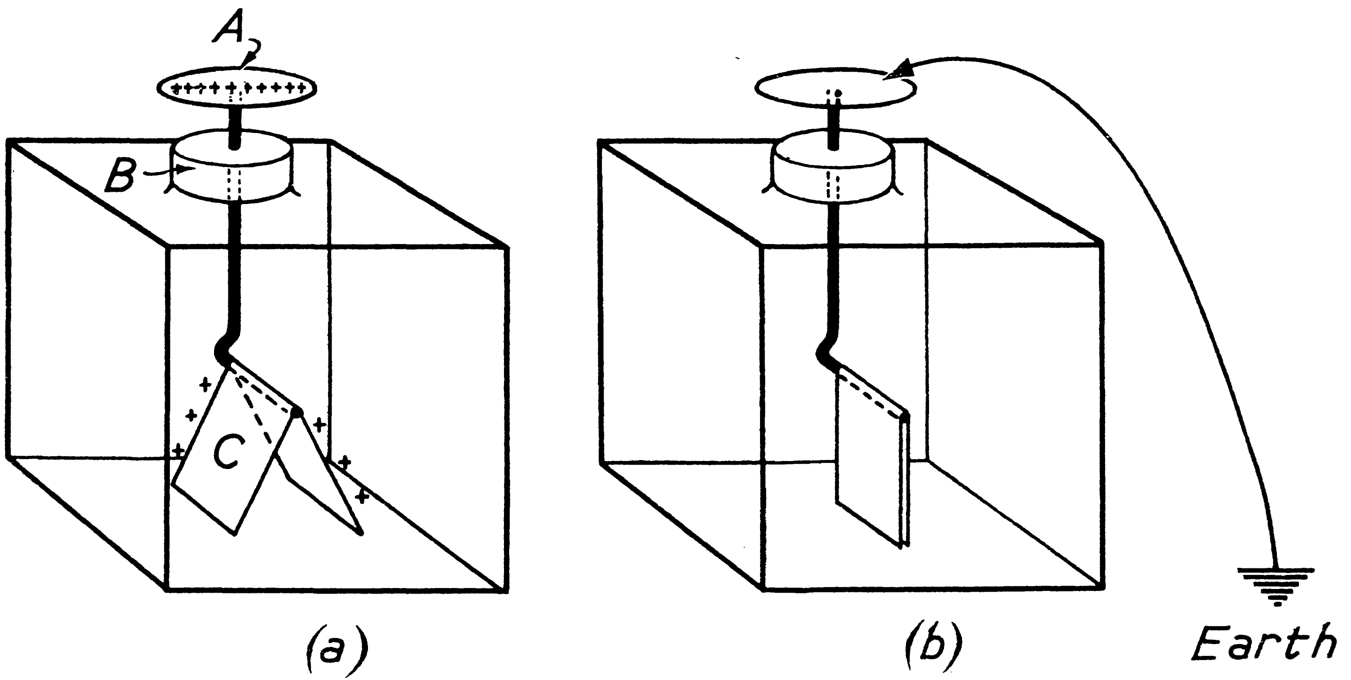

FIG. 23. THE GOLD-LEAF ELECTROSCOPE

(*a*) Electroscope charged. (*b*) Electroscope discharged. *A*, conducting plate; *B*, insulating collar of ebonite or sulphur; *C*, thin gold leaf. In (*a*) the leaves are both charged positively, and therefore repel each other. In (*b*) the charge has been led away to earth by a conducting wire. Negative ions in the vicinity will also neutralize the charge.

that at this altitude ionization was still considerable. Hess, who continued the work, found that it actually increased, and concluded from his results that some new kind of radiation was entering the atmosphere from outside. He argued that even if the conductivity of air was caused by the presence in it of minute traces of radio-elements, at 13,000 feet the atmosphere would be so tenuous as to reduce the density of ions considerably. Hence the rate of leakage should have declined appreciably, whereas in actual fact a marked increase took place.

During the next few years some further contributions of value were made by Kolhörster, who demonstrated the highly penetrating nature of the rays—a hundred times more penetrating than the 'hardest' γ-radiation, that of thorium C. By early 1915, however, investigation ceased on this, as on other researches, and there ensued a decade of comparative stagnation.

Distribution of the Radiation

In 1927 a most important observation was made by the Dutchman Clay, who, while on a journey to Java from the Netherlands, investigated cosmic-ray activities in various latitudes. His observations indicated that the intensity was greater in northern latitudes than at the equator. This latitude effect, soon confirmed by others, could mean only one thing—that cosmic rays were, in part at least, composed of charged particles which suffered deviation when cutting vertically through the earth's magnetic field. The magnetic force would tend to sweep particles of less than a certain speed away from the equator towards the magnetic poles, and thus result in a reduced intensity at the equator. About this time, too, as a result of a considerable number of investigations by many authors, more definite conclusions

began to emerge concerning the variation of cosmic-ray intensities with altitude. It appeared that fundamentally there exist two types of primary rays carrying electrical charges (apart from possible photons and neutrons). The first type is extremely penetrating; its effect can be measured on sealed recording electroscopes submerged half a mile under water. The second is less so, and is the component whose variation accounts for the latitude effect. This 'soft' radiation is now known to consist of electrons moving with energies between one million and one thousand million volts.

In recent years progress has come about largely by the development of extraordinarily sensitive instruments for studying the behaviour of individual particles—instruments invented originally for the study of radioactivity phenomena. They are already familiar to us as the Wilson chamber and the Geiger counter. This latter instrument has undergone many improvements in the years since its inception, and in its improved form, known as the Geiger-Müller counter, is capable of counting many thousands of particles per minute. Furthermore, the pulses it delivers may be amplified by means of thermionic valves and made to actuate an electron beam in a cathode-ray oscillograph (as in Thomson's apparatus, p. 25), the resultant deflection being photographed. Alternatively, an amplified pulse may be set to operate the cloud-chamber expansion and take a photograph of the particle causing the pulse. Usually two counters are 'triggered' together and placed in line with the cloud chamber. The rays must then pass through both counters arranged, say, vertically before the expansion mechanism can operate. Such an arrangement enables directionality of the rays to be studied. A further modification, known as the proportion counter, distinguishes between alpha particles which ionize heavily and beta particles which ionize much less.

The Positron

It was during an investigation of cosmic-ray tracks that Anderson first discovered the positron. In his experiment a lead plate about one-quarter of an inch thick was arranged in the middle of a Wilson chamber placed between the poles of a powerful electromagnet. The effect of this magnetic field was to curve the tracks of any charged particle which might enter the chamber as a result of cosmic-ray activity in the vicinity. One of his photographs showed a track which bent in the opposite direction to that expected of an electron (Fig. 24). It might be thought that this indicated merely the motion of an electron in the opposite direction to that supposed, since its origin and direction of motion depended on the chance penetration of a cosmic ray which might be moving in any direction. However, on passing through a lead sheet a charged particle will be slowed down; and, as a consequence, on emerging it will have a greater curvature in the magnetic field than before entering. From the change in curvature Anderson was able to tell the direction of motion of his particle, which, in conjunction with the direction of deflection, showed that the particle carried

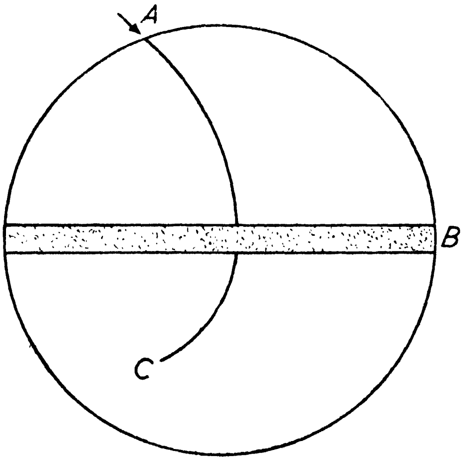

FIG. 24. THE DISCOVERY OF THE POSITRON

Track of positron in magnetic field. Since the track C has greater curvature than track A, the positron must be moving more slowly along C than A, and hence must have originated at A.

a positive charge. Further, from the extent of penetration and nature of cloud track it could not be a proton (which ionizes heavily and produces a dense track, as does an alpha particle), but must have a much smaller mass. It has since been demonstrated that its mass is within 1 per cent. of that of the electron. Assuming the mass of this particle to be exactly equal to that of the electron, which seems probable, the track which Anderson photographed corresponded to a particle of 63 million electron volts of energy. More recently photographs have been obtained of electron-positron pairs produced by the interaction of a million-volt photon with an atom. The rest mass of each particle is (by the Einstein equation) 500,000 e.v. In this reaction the atom appears to act merely as an intermediary enabling the photon to undergo transformation. It will be noticed that the electric charge is conserved in the transformation, for equal and opposite charges are carried by the electron and positron respectively.

A curious feature about the positron, and one which still awaits an explanation, is that in presence of matter it cannot remain long in the free state. Within a period of 10^{-8} seconds it disappears either into an atomic nucleus or by reacting with an electron to produce two photons. Such a transient existence explains in part the delay in recognizing it.

Showers

An interesting phenomenon was recorded by Blackett and Occhialini in 1936—namely, the occurrence of showers of particles which appeared to originate in the walls of the cloud chamber at a single point. Bethe and Heitler have shown that the phenomenon is completely in accord with the supposition that the cosmic particle causing the shower is a fast electron. Theory indicates that several high-energy

photons are produced when an electron of 10^8 e.v. or more is slowed down by passing through the extra-nuclear field of an atom. These photons travel on for a short distance through matter, but each one soon transforms into an electron-positron pair, and although each of these particles has less energy than the original they may still be fast enough to repeat the process of photon creation. Thus a cascade ensues, and multiplication continues until the particle energies fall below a certain value. When this happens the residual energies are dissipated in ordinary scattering processes. It has been found that shower production can quite readily be regulated by placing in the chamber a number of thin plates of some dense material such as lead (Fig. 25). A thin plate, while providing the necessary concentration of atoms to ensure a single stage of the process occurring, is not sufficient for a succession of such stages.

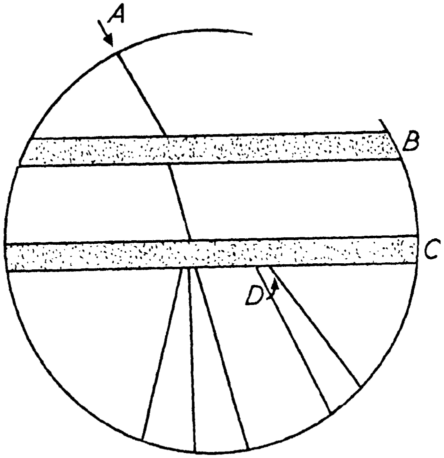

FIG. 25. COSMIC-RAY SHOWERS

The diagram shows creation of cosmic-ray showers by the incoming fast electron *A*. *B* and *C* are thin lead plates. *D* shows positron-electron pair produced by a photon given out at plate *B* by the original electron, and interacting with a lead atom in plate *C*.

The Meson

In 1936 Anderson appeared once more in the story with the discovery of another new particle, this time in the highly

penetrating component of cosmic rays. For a long time it had been known that this component consisted of particles charged with very high energy, and from their behaviour in the cloud chamber it was deduced that they too carried unit electronic charge. But their behaviour was not quite that of ordinary electrons; in particular, they were absorbed very much less readily in matter than electron theory predicted. There was no possibility of theory being at fault, because, as we have seen, particles of high energy had been observed which did behave according to expectation. But neither could they be protons, despite their great penetrating power, for they gave tracks characteristic of electrons. Anderson suggested, therefore, that a new particle was concerned—one having the same charge as an electron, but a mass intermediate between that of electron and proton (1840 electron masses). Absorption experiments indicate that the mass of this intermediate particle, or meson, is about 200 electron masses, although its exact value is not yet known with any certainty.

Almost immediately it was pointed out that two years earlier Yukawa, from purely theoretical considerations, had deduced the existence of such a particle. Yukawa formulated a theory of the atomic nucleus to explain the close-range attractive forces which experiment had revealed (p. 102). In order to do so he had found it necessary to modify the fundamental equations of electromagnetism, for he saw that they could not lead to the type of force giving the necessary rapid fall-off with distance that he required. He obtained an equation for his nuclear field of force, and then proceeded to introduce quantum conditions as had been done in the past for the electromagnetic field. Now just as the light packet, or photon, results from the latter process, so Yukawa found another unit of energy in his quantized nuclear field. But this unit was found to be a

particle—that is to say, unlike the photon, it had a rest energy, or mass. It so happens the value he obtained for his mass was of the same order as that found for the mesons of cosmic radiation, which suggests that they are one and the same particle. On the meson theory of nuclear forces, binding between the proton and neutron of deuterium would be brought about by the continual interchange of a positive meson between the two particles, whereby the proton would become a neutron and the neutron a proton. There is some inconclusive evidence for the existence of positive, negative, and neutral mesons, and also distinct evidence that mesons undergo spontaneous radioactive decay in the free state, emitting electrons or photons and disappearing within a period of 10^{-6} second. This behaviour is also in accordance with Yukawa's theory.

Owing to their rapid decay mesons cannot be part of the initial cosmic rays, which presumably have travelled through ages of time, but must be formed in the upper atmosphere by the true primary particles. These, on present views, are considered to be protons having energies up to 10^{17} e.v. It is possible, however, that there may be in addition to these alpha particles and neutrons. For the true primary particles to knock out mesons by collision with atomic nuclei they must certainly have energies greater than the rest energy of the meson itself—namely, a hundred million volts. It is doubtless significant that almost all the penetrating cosmic rays have energies above this value. When the meson's energy falls below about 2×10^8 e.v. it seems to disintegrate to electrons, which constitute the secondary (soft) component of cosmic rays.

The Betatron

Until recently it had not been found possible in the laboratory to accelerate electrons to such velocities, but

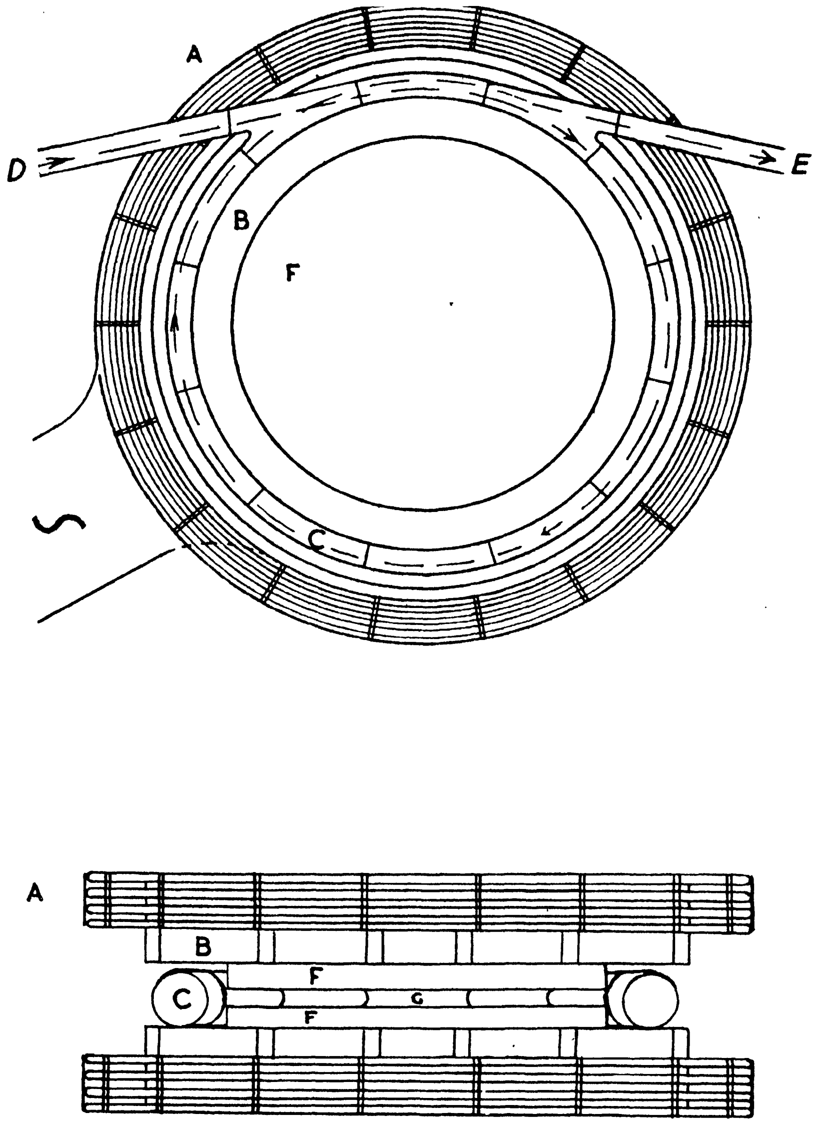

FIG. 26. DIAGRAM OF THE BETATRON

Schematic outline in plan and elevation. *A*, magnetizing coil; *B*, magnet; *C*, vacuum tube, built up in sections; *FF*, centre pieces; *G*, gap. Electrons enter at *D*, circle the vacuum tube a considerable number of times, and leave at *E*. The electrons are accelerated during the time the magnetism is increasing—that is, during the first quarter-cycle of the current. Note narrow gap (*G*) between pole faces within the orbit.

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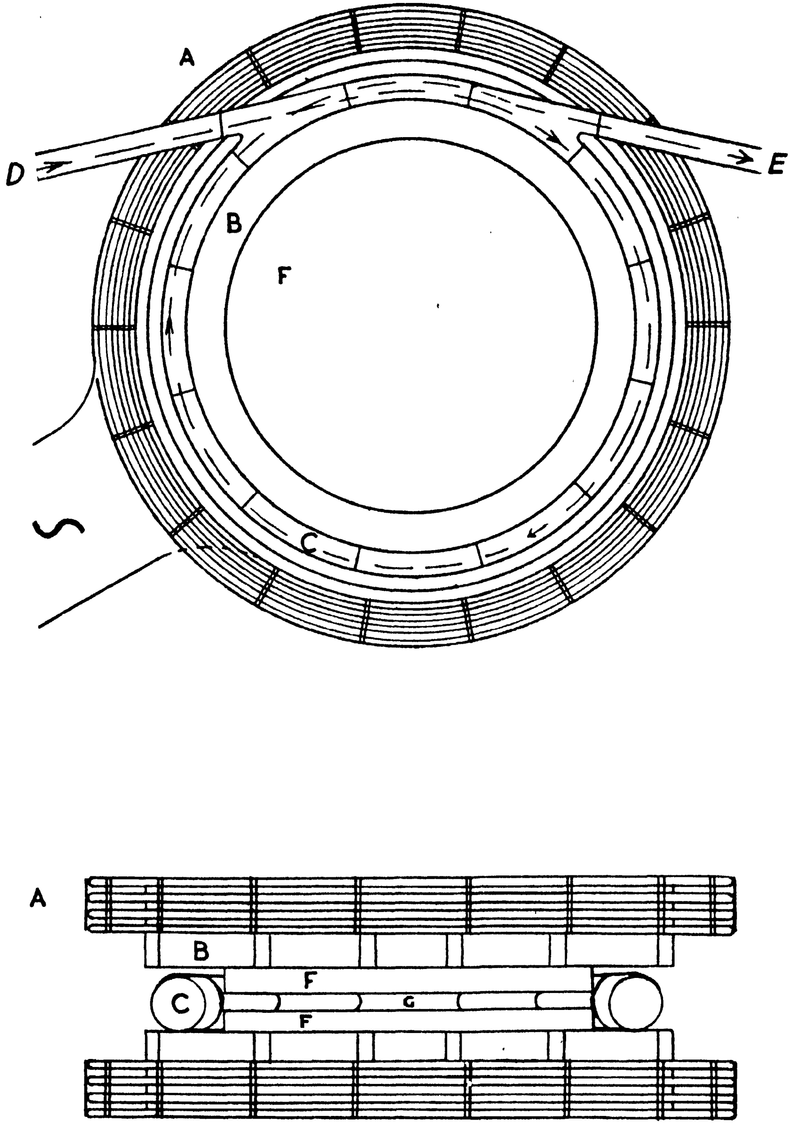

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little too early it encounters in the dees an electric force *accelerating* its motion. For then it will suffer a relativity mass increase, without perceptible increase in velocity (which will be, practically, the limiting velocity '*c*' for energies above 300 M.e.v.), and this increase in mass will cause its orbit to enlarge and the particle to lag. The phase of the particle is thus automatically synchronized with that of the alternating e.m.f. Now if the frequency is slowly decreased the particles will assume a succession of stationary orbits of gradually increasing radius and energy. This change of frequency is proposed as the best way of accelerating positive particles. But the synchrotron should also be able to accelerate electrons, although here an increasing magnetic field with a constant alternating frequency on the dees would be more practicable. It is expected that energies of 1000 M.e.v. will be attained by such means. Instruments based on this principle are at present being built in various laboratories.

It is to be expected that both the betatron and the high-voltage cyclotron will enable many of the phenomena associated with cosmic-ray matter interactions to be reproduced and studied in the laboratory. Such an experimental approach to the problems of nuclear structure is, we may feel sure, likely to reveal in the future secrets as strange and fascinating as any that have been discovered in the past. But there are still many difficulties associated with meson theory, and a survey of present-day sub-atomic physics, with its increasing number of supposedly primary particles, each merely (from one point of view) an *ad hoc* device with which to parcel up distinct groups of facts, leaves the spectator feeling that the formulation of a unitary theory of matter is farther from accomplishment now than at any time since Prout.

GROUP 7	GROUP 8		
9. Fluorine F 19·00			
17. Chlorine Cl 35·46			
Manganese Mn 54·93	26. Iron Fe 55·84	27. Cobalt Co 58·94	28. Nickel Ni 58·69
35. Bromine Br 79·92			
Masurium Ma (?)	44. Ruthenium Ru 101·7	45. Rhodium Rh 102·91	46. Palladium Pd 106·7
53. Iodine I 126·92			
Rhenium Re 186·31	76. Osmium Os 190·2	77. Iridium Ir 193·1	78. Platinum Pt 195·23
Neptunium Np 239	94. Plutonium Pu 239	95. Americium	96. Curium

n with much greater accuracy than others.

GLOSSARY OF TECHNICAL TERMS

Action. In dynamics is measured by the product of energy × time.

Alpha (α-) *Particle.* A helium atom which has lost its two outer electrons. Has a mass of four units compared with hydrogen unity, and carries a charge equal to twice that carried by the electron, but of opposite sign.

Alpha (α-) *Rays.* A stream of alpha particles. Emitted spontaneously by certain elements of high atomic weight.

Atom. The smallest unit of an element which can take part in chemical change. Consists of a minute nucleus containing most of the mass, and positively charged, surrounded by electrons of opposite sign. The normal atom is electrically neutral.

Atomic Number. The number of positive charges on the nucleus of the atom. Hence equal in a neutral atom to the number of outer electrons.

Atomic Weight. The relative weight of the atom of an element compared with oxygen (^{16}O = 16·0000).

Avogadro's Principle. Equal volumes of gases under identical conditions of temperature and pressure contain the same number of molecules.

Beta (β-) *Particle.* An electron emitted by a radioactive atom, sometimes with a velocity nearly equal to that of light.

Beta (β-) *Rays.* A stream of beta particles. See *Alpha* (α-) *Rays.*

Betatron. An instrument for accelerating electrons to high voltages by means of a changing magnetic field.

Binding Energy. The amount of energy involved in holding together the protons and neutrons constituting the nucleus. By Einstein's Principle this is measured by the mass difference of the nucleus and the sum of the proton and neutron masses it contains.

Chain Reaction. A reaction in which particles causing atomic disintegration are regenerated and used in further disintegrations.

Compound. A chemical compound consists of molecules—that is, composite structures made up of atoms. All the molecules of any particular compound contain the same number of atoms arranged in the same way.

Conservation of Energy. According to the classical nineteenth-century doctrine energy could be neither created nor destroyed, but merely transformed. Consequently in any isolated system the total amount of energy remained constant.

Conservation of Mass. Classical mechanics maintained that matter could be neither created nor destroyed. In a chemical change, for example, where none of the reactants was allowed to escape, the weight of matter after the change was equal to the weight before the change.

Conservation of Mass Energy. Relativity theory states that in any change in an isolated system the total amount of mass energy remains constant, although neither mass nor energy is separately conserved. Mass is a concentrated form of energy. Alternatively, energy is a diffuse form of mass. The two aspects are connected by the relation $E = mc^2$, where E is energy measured in ergs, and m is mass measured in grams.

Cosmic Rays. Radiation consisting of high-energy particles of unknown origin, which reach the earth equally from all directions of the universe.

Cross-section. The apparent cross-sectional area of a nucleus as deduced from experiments involving either absorption or scattering of atomic particles. The normal value is about 10^{-24} sq. cm.

Cyclotron. An instrument for accelerating positively charged ions to high voltages by means of a potential alternating in step with the ions, which are themselves moving in circular orbits under the influence of magnetic forces.

Deuteron. The nucleus of the deuterium atom, consisting of a proton and a neutron tightly bound together (symbol: ${}^{2}_{1}D$).

Diffusion. The motion of the molecules (*q.v.*) of a gas or liquid under the influence of random collisions.

Discharge-tube. A vessel, usually of glass, evacuated of air and containing metal components, or electrodes, between which a high voltage can be applied. The residual air between the electrodes ionizes (*q.v.*) under the influence of the electrical stress and becomes conducting.

Disintegration. The breakdown of an atomic nucleus, either

spontaneously or as the result of impact with a projectile of atomic dimensions.

Electron. The naturally occurring unit of negative electrical charge. Electrons are present in the outer layers of the atom, from which they may be removed. The outer electrons are responsible for all chemical changes. Beta rays are electrons ejected from atomic nuclei. Their mass is $\frac{1}{1840}$ that of the proton.

Electron Volt (*e.v.*). The amount of energy which an electron or other singly charged particle acquires when accelerated between two points, between which there is a difference of potential of one volt. This increased energy appears as an increase in speed. 1,000,000 e.v. is written 1 M.e.v. Where no confusion can arise an energy of so many 'volts' is often referred to.

Element. An elementary substance composed of atoms all having the same atomic number (*q.v.*).

Energy. Capacity for doing work in the scientific sense—*e.g.*, raising a weight against the force of gravity or overcoming friction.

Fission. The splitting of an atomic nucleus into two or more approximately equal fragments with liberation of residual units of mass (neutrons) and gamma rays.

Frequency. The number of times per second that an action—*e.g.*, a rotation or vibration—is repeated.

Gamma (γ-) *Ray.* Electromagnetic radiation akin to light, but of much higher frequency (shorter wavelength). Not deflected by electrical or magnetic forces.

Gas. A state of matter in which the molecules are separated by distances large compared with their dimensions. These molecules are in a state of constant motion and collision, their speeds increasing with rise in temperature.

Geiger Counter. An apparatus consisting of an outer metal cylinder and an inner concentric wire insulated from the cylinder. The wire is given usually a high positive charge. When an ion enters the chamber it ionizes other atoms, which causes a breakdown in the insulation between wire and wall. As a consequence a heavy current flows momentarily.

Half-life (*T*). The time taken for a radioactive substance to fall to half-strength, which is characteristic of that particular element.

Hydrogen. Symbol H or ^1_1H. The lightest element known. Its atom consists of a nucleus (the proton) and one outer electron.

Inertia. The resistance offered by a massive body to being moved.

Ion. An atom which has lost or gained one or more electrons and is therefore electrically charged either positively or negatively.

Ionize. To render conducting to an electric current by the creation of ions.

Isotope. A variety of a particular element, having the characteristic nuclear charge and chemical properties, but differing in mass from other varieties of the same nuclear charge.

Kinetic Energy. Energy of motion, measured by the product of half the mass and the square of the velocity ($K.E. = \frac{1}{2}mv^2$).

Mass. Quantity of matter. Measured scientifically, usually in grams.

Mass Spectrograph. An instrument for analysing positively charged particles according to their mass by means of combined electrical and magnetic attraction.

Meson. A radioactive particle intermediate in mass between electron and proton, which has only a fleeting existence.

Molecule. The smallest unit of a chemical compound which is capable of an independent existence.

Momentum. Quantity of motion. Measured by the product quantity of matter $\times$ velocity, or mv.

Multiple Proportions. A law, enunciated by Dalton, which states that when two elements combine with each other to form more than one compound, the ratio of the quantities combined in the first compound is simply related to the ratio for the second.

Neutron. An elementary particle of dimension and mass nearly that of the proton but without electrical charge.

Nucleus. The atomic nucleus has a diameter of approximately 10^{-12} cm. and is composed of neutrons and protons. It carries a net positive charge equal to the total number of protons it contains.

Packing Fraction. The percentage fractional loss in mass per unit particle due to energy loss on coalescence.

Periodic Law. If all the elements are arranged in rows in order of ascending atomic weight, then a periodic variation in properties may be observed, such that elements with similar properties tend to recur at regular intervals.

Photon. Radiation (*q.v.*) is not emitted continuously, but only in the form of discrete quantities known as 'quanta' or

'photons.' Thus, for example, gamma rays consist of photons which in some respects behave as particles.

Positron. A particle equal in mass to the electron, and carrying a charge equal in magnitude, but opposite in sign.

Potential Energy (Mechanics). Energy which a body possesses in virtue of its position—*e.g.*, the energy of a coiled spring or of a body raised above the ground.

Potential (Electrical). The work which must be done (and hence energy acquired) to move unit electrical charge from infinity to the object at that potential.

Plutonium. Element of atomic number 94, prepared by decay of uranium 238 consequent on slow-neutron capture.

Proton. A fundamental particle of mass 1·0081. ($^{16}_{8}O = 16{\cdot}0000$.) Absolute mass $1{\cdot}673 \times 10^{-24}$g. The proton carries a positive charge equal in magnitude to the negative charge carried by the electron. It is the nucleus of the hydrogen atom from which it is prepared by stripping off the single outer electron —*i.e.*, ionizing the atom.

Quantum of Action, Planck's. Symbol, h. Radiant energy of frequency ν behaves as if it were composed of discrete bundles of energy E of magnitude given by $E = h\nu$, where $h = 6{\cdot}624 \times 10^{-27}$ erg second.

Quantum Tunnel Effect. The effect whereby a charged particle may pass through the nuclear potential barrier, although according to classical physics it has insufficient energy to surmount the barrier.

Radiation. Energy in the form of electromagnetic vibrations, such as wireless waves, radiant heat, light, X-rays, gamma rays.

Radioactivity. Instability of the atomic nucleus resulting in the emission of charged particles, neutrons, or gamma rays.

Relativity, Theory of. A reformulation of Newtonian dynamics which originated in the failure to detect velocities greater than that of light.

Resolving Power. Of a mass spectrograph or cyclotron is measured by the effectiveness of separation of two beams of isotopes originating at the same source.

Resonance Capture. Atomic particles of a critical velocity may be absorbed strongly by the atomic nuclei of a particular element, whereas for velocities greater or less the absorption may be negligible. Every species of nucleus is in general

characterized by many such absorption levels. The phenomenon is associated with the wavelike nature of primary particles.

Transuranic Elements. Elements of atomic number greater than that of uranium. There are four known at present—No. 93 (neptunium), No. 94 (plutonium), No. 95 (Americium), and No. 96 (Curium).

Uranium. The heaviest of the elements which are known to occur naturally on the earth. Atomic number, 92. Feebly radioactive.

Valency, or Valence. The number of atoms of hydrogen which an atom of the element concerned can combine with, or displace from, another compound. A property determined by the outer ring of planetary electrons.

Wave Mechanics. A description of extra-nuclear phenomena founded on classical principles, in conjunction with an assumption that electrons are associated with waves.

X-rays. Electromagnetic radiation of frequency intermediate between that of light and gamma rays. Produced by electron impacts of high energy.

Zinc-sulphide Screen. Used as a detector for sub-atomic particles. Microscopic examination reveals that the screen is composed of minute crystals of zinc sulphide. A single alpha particle is sufficient to split one of these crystals, and during the process there occurs a minute flash of visible light, or scintillation.

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